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Using quantitative data on postural activity to develop methods to predict and prevent cybersickness

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In this article, we discuss general approaches to the design of interventions that are intended to overcome the problem of cybersickness among users of head-mounted display (HMD) systems. We note that existing approaches have had limited success, and we suggest that this may be due, in part, to the traditional focus on the design of HMD hardware and content. As an alternative, we argue that cybersickness may have its origins in the user's ability (or inability) to stabilize their own bodies during HMD use. We argue that HMD systems often promote unstable postural control, and that existing approaches to cybersickness intervention are not likely to promote improved stability. We argue that successful cybersickness interventions will be designed to promote stability in the control of the body during HMD use. Our approach motivates new types of interventions; we describe several possible directions for the development of such interventions. We conclude with a discussion of new research that will be required to permit our approach to lead to interventions that can be implemented by HMD designers.

KEYWORDS

cybersickness, virtual reality, postural stability, movement, motion sickness, posture

1 Introduction

In this paper, we discuss the most persistent impediment to the growth of virtual reality (VR) technologies: Cybersickness. Efforts to address the problem of cybersickness commonly are referred to in terms of mitigation; however, there is not a formal, universally-accepted definition of mitigation in relation to cybersickness. Broadly, the term refers to reduction in the extent to which cybersickness is a problem for users of VR. We avoid the term, mitigation, because, by definition, mitigation refers to the alleviation of an existing problem. Our approach focuses upon the prevention of cybersickness: Problems that can be avoided do not require mitigation. In this article, we use cybersickness intervention to designate a superordinate category comprising techniques for the prediction, prevention, and mitigation of cybersickness. Our focus is on cybersickness in head-mounted display (HMD) systems; however, it may be possible to apply our approach to additional types of VR technologies.

One common problem is that many cybersickness interventions are applied to all users. Such techniques are not *tailored*, that is, they do not distinguish between users who are at risk for cybersickness and those who are not at risk. This issue is particularly important given the finding that existing cybersickness interventions can reduce the user's sense of presence, or even degrade user performance (e.g., Bala et al., 2018). The development of cybersickness interventions that are tailored such that they are applied only to at-risk individuals can significantly improve user experience for persons who are not at risk (Zielasko et al., 2017).

Another problem is that many cybersickness interventions are visible to users. By *visible*, we mean that a cybersickness intervention requires or entails some aspect of the user's conscious awareness. As one example, many cybersickness interventions depend upon conscious user inputs, such as symptom ratings, or responses to questionnaires (e.g., Gavgani et al., 2018; Thorp et al., 2022). As another example, many cybersickness interventions modify display characteristics in ways that sometimes are consciously noticed by users, such as field of view restrictions (e.g., Groth et al., 2021), or teleporting (e.g., Bozgeyikli et al., 2016).

In this article, we provide general descriptions of cybersickness interventions that have the potential to be both tailored, such that they are applied only to users who are at risk for cybersickness, and invisible, such that they do not influence conscious user experience or require conscious user input or influence conscious user experience. We propose examples of new cybersickness interventions that may meet these criteria. Some of our proposed interventions could improve the prediction of cybersickness in individuals. Such prediction would make it possible for cybersickness interventions to be implemented on an individual basis, only for users who could benefit from them. We also propose new cybersickness interventions that offer the potential to *prevent* cybersickness in individuals who are at risk, thereby avoiding the need for mitigation. For designers and users, our approach has an especially significant advantage. Because our interventions can be invisible, users need never be aware that we are collecting data, and the user experience need not be interrupted (e.g., by the need to provide subjective ratings), or altered (e.g., by visible degradation of the display or interaction).

The problem of cybersickness is not new, and is widely recognized by developers and among researchers in both the applied and basic science communities (e.g., Sharples et al., 2008; Zielasko et al., 2017; Stanney et al., 2020b). Accordingly, in this article we do not attempt a comprehensive review of cybersickness interventions. There also have been many treatments of the ongoing debates about the etiology of cybersickness (e.g., Stoffregen and Riccio, 1991; Palmisano et al., 2020; Stanney et al., 2020b), which we do not recapitulate here. Rather, in this article our aim is to present a new approach to the design of cybersickness interventions. Our approach is derived from the conceptual foundations of the Ecological Approach to Perception and Action (e.g., Gibson, 1966; Gibson, 1979), and from the conceptual and empirical literatures relating to the postural instability theory of motion sickness etiology (Riccio and Stoffregen, 1991; Stoffregen and Riccio, 1991). However, for the VR community the value of our approach will be determined by the success of interventions that can be derived from it. Such interventions will stand or fall regardless of their relevance to any theory of cybersickness etiology. It is important to understand that our purpose in this article is not to provide concrete examples in sufficient detail that they could be implemented. Rather, our aim is to argue that interventions of the type we describe are motivated by existing theory and empirical research, such that it could be highly valuable for applied researchers and designers to pursue our approach. As will be explained in Section 5, more research will be required to guide the design of specific interventions. We believe that much of the required research can be conducted by the designers and developers of VR systems, with existing technology and with very little additional effort.

2 Selective summary of current trends

Cybersickness is common among users of desktop console video games (Stoffregen et al., 2008; Dong et al., 2011; Chang et al., 2017), HMDs (Merhi et al., 2007; Munafo et al., 2017), projection video systems (Villard et al., 2008), and even tablet computers (Stoffregen et al., 2014). Cybersickness has been documented in both adults and children (Chang et al., 2012). It has often been suggested that full development of VR technology naturally will lead to the disappearance of cybersickness (DiZio and Lackner, 1997). Yet both anecdotal reports (e.g., Boyd, 2014) and controlled research indicate the opposite effect: With "advances" in VR technology, cybersickness is not going away. No one ever got sick playing *PacMan*, but contemporary HMD systems commonly induce cybersickness in more than 40% of users (e.g., Sharples et al., 2008; Munafo et al., 2017; Curry et al., 2020). Existing evidence suggests that, with respect to cybersickness, the current generation of HMD technologies is not better than preceding generations (Stanney et al., 2020b).

Cybersickness is most commonly related to virtual locomotion (Bruder et al., 2012; Nilsson et al., 2018). For example, among users of an HMD (Oculus Rift), cybersickness was significantly more common during a virtual locomotion game than during a game that did not include virtual locomotion (Munafo et al., 2017). Accordingly, our analysis and recommendations focus on interventions for cybersickness relating to virtual locomotion.

2.1 Individual differences in susceptibility

It is well-established that the risk of cybersickness can be influenced by aspects of VR technology (e.g., Rebenitsch and

Owen, 2016). At the same time, a central fact of cybersickness is the existence of individual differences in susceptibility. In any given setting, some individuals get sick while others do not (for a rare exception, see Merhi et al., 2007; Experiment 2). Comparison across VR platforms suggests that the risk of cybersickness is more strongly related to individual differences than to differences between technological platforms (Sharples et al., 2008). Moreover, multiple studies report very high inter-individual variability in symptom ratings (e.g., Sharples et al., 2008; Dong et al., 2011; Stoffregen et al., 2017b; Curry et al., 2020). These findings indicate that cybersickness cannot be accounted for exclusively in terms of the hardware or software of VR systems. We suggest it is more appropriate (and will be more successful) to address cybersickness, not as a phenomenon of a technology, but as a phenomenon of human-machine systems (Stoffregen et al., 2006b; Flach et al., 2018; Hancock et al., 2018; Smart et al., 2020).

Many factors have been found to influence individual differences in cybersickness. Examples include posture (i.e., sitting vs. standing; Merhi et al., 2007), whether or not the individual is in control of the stimulus (e.g., Sharples et al., 2008; Dong et al., 2011; Chen et al., 2012), variations in the nature of user control (e.g., Stoffregen et al., 2014), the user's age (e.g., Arns and Cerney, 2005) gaming experience (e.g., Chattha et al., 2020; Weech et al., 2020), and even personality type (Widyanti and Hafizhah, 2021).

One factor that is widely reported to influence cybersickness is sex. In many settings, women are more likely to experience motion sickness than men. In survey research, this sex difference has been documented on ships at sea (Lawther and Griffin, 1986), in buses (Turner and Griffin, 1999), in laboratory devices (Koslucher et al., 2015), and even in motion sickness associated with wind-blown movement of tall buildings (Lamb et al., 2013). In addition, women are more susceptible than men in VR. As two examples, women were more susceptible than men when seated participants played an ambulatory virtual locomotion game presented through a head-mounted display (Munafo et al., 2017; Experiment 2), and women were more susceptible than men when driving a virtual automobile presented through a desktop monitor (Stoffregen et al., 2017).

While sex differences in cybersickness are common, they are not universal. In several studies, sex differences in susceptibility did not reach statistical significance (Munafo et al., 2017, Experiment 1; Clifton and Palmisano, 2020; Curry et al., 2020). In part for this reason, the true extent of sex differences in cybersickness is the subject of lively debate (e.g., Grassini and Laumann, 2020; Stanney et al., 2020a; Stanney et al., 2020b). Additional research is needed to understand the circumstances under which cybersickness differs between women and men (Munafo et al., 2017; Curry et al., 2020). Among other things, new research is needed on how cybersickness may differ in gay, lesbian, trans, and non-binary populations. We understand that some of these groupings are biological (e.g., reproductive anatomy), while others are behavioral (e.g., sexual preference): It is an empirical question the extent to which each might influence susceptibility to motion sickness. However, it is clear that sex can be a factor in individual differences in cybersickness susceptibility.

2.2 Contemporary trends in cybersickness intervention: Re-designing the product

There is an increasing body of research on cybersickness interventions. Some of this research has taken place in industry settings, and is proprietary, or has not been subjected to peer review. In this article, our focus is on publicly available research, most of which is in peer-reviewed journals and conference proceedings. Our review of the available literature suggests that most existing cybersickness interventions are focused on 1) reducing the risk of cybersickness through changes in the design of VR technology, or 2) predicting cybersickness through the collection of user data. In this section, we address the first of these trends. We address the second in a later section.

Stanney et al. (2020b) provided a representative cross-section of contemporary academic research relating to cybersickness. Their review focused on etiological theories, and cybersickness interventions inspired by etiological theories. By contrast, many cybersickness interventions have not been based upon specific etiological theories. For example, some cybersickness interventions have been derived from areas of the basic science literature not related to cybersickness (e.g., Keshavarz and Hecht, 2012; Jasper et al., 2020; Kemeny et al., 2020). However, the larger category of nominally atheoretic cybersickness interventions have been developed directly from aspects of VR software and hardware (e.g., Nilsson et al., 2018).

2.2.1 Prevention through software re-design

2.2.1.1 Teleporting

As noted in an earlier section, cybersickness is widely associated with virtual locomotion (Bruder et al., 2012; Nilsson et al., 2018). Teleporting, that is, instantaneous movement from place to place within a virtual environment, is useful in many applications. Some researchers have suggested that the established technique of teleporting might be used to reduce cybersickness by eliminating the translational components of virtual locomotion. A common approach is to avoid continuous visual representations of motion by requiring the user to teleport in the virtual environment (e.g., Bozgeyikli et al., 2016). Several variants on this theme have been explored, such as "viewpoint snapping" (Farmani and Teather 2018), "jumping" (Weissker et al., 2018), and "blinking" (Habgood et al., 2018). Some researchers have noted a reduced incidence of cybersickness when smoothed virtual motions were presented during the virtual traversal of terrain that would normally afford a bumpier trajectory (Dorado and Figueroa 2014). As another approach to minimizing optical flow cues, it has been proposed to apply a Gaussian blur to the entire field of view during rapid movements (Budhiraja et al., 2017). Teleporting can reduce cybersickness (but see Clifton and Palmisano, 2020), but the technique has several disadvantages. Teleporting can be tedious for users, and lead to diminished spatial awareness (Bowman et al., 1997). By eliminating the optical consequences of locomotion, teleporting degrades the user experience (e.g., by reducing vection and/or presence); in this sense, teleporting defeats the purpose of the technology. As noted by Zielasko et al. (2017), "reducing cybersickness and increasing presence often seem to be competing goals . . . [teleportation] is used by a lot of current applications and games even though it reduces presence, which at the end is the main driver for using a VR system in the first place". From our perspective, a larger problem is that teleporting is not "invisible". On the contrary, the difference between teleporting and naturalistic locomotion is highly conspicuous.

2.2.1.2 Restricting the field of view

Dynamic FOV restriction has become one of the most widely used cybersickness interventions (e. g., Kim et al., 2008; Carnegie and Rhee, 2015; Fernandes and Feiner 2016; Kim et al., 2018; Groth et al., 2021). Generally, this technique is based on the hypothesis that peripheral optical flow is an aggravating factor for cybersickness. The use of FOV restriction in mitigating cybersickness has had mixed results (e.g., Moss and Muth 2011; Bala et al., 2018; Norouzi et al., 2018). In particular, restriction may not be desirable in the nasal portion of the FOV, to the extent that it occludes the ground plane and horizon line (Kim et al., 2018). Restriction of the field of view can be limited to certain portions of the scene; for example, leaving fully visible the depicted ground (Wu et al., 2021). Perhaps the most straightforward problem with FOV restriction as a cybersickness intervention is that it defeats the purpose of contemporary display systems, which are deliberately designed to have larger—rather than smaller—FOV.

2.2.1.3 Stable visual referents

It has been suggested that cybersickness may be reduced when virtual displays contain stable visual referents. This idea has commonly been interpreted through the concept of "rest-frames" (Prothero et al., 1999). Some studies have reported reduced cybersickness when an HMD display included a stable visual referent (Cao et al., 2018). A recurrent problem with research and development in this area is the lack of consistency in defining (and implementing) stable visual referents. The problem can be stated succinctly: Stable relative to what? Should the visual referent be stable relative to the physical Earth? Relative to a hypothetical sensory reference frame? Both of these have been proposed, sometimes within the same article (e.g., Cao et al., 2018). These two conceptualizations are compatible only under certain assumptions about the nature of perception (e.g., Stoffregen and Riccio, 1991). At the same time, other authors have proposed "rest frames" that are (visibly) stable relative to the user's head, as in the concept of a "virtual nose" (cf. Bonato et al., 2015; e.g., Wienrich et al., 2018). Visual elements that are stationary relative to the user's head cannot be stable relative to the Earth, and *vice versa*. This confusion, which is qualitative, can only inhibit the development of truly useful cybersickness interventions. In a later section, we offer an interpretation of stable visual referents that is logically consistent with our theoretical perspective.

Teleporting, restricted FOV, and the use of stable visual referents each have the advantage that they can be tailored, that is, applied to individual users. It is a simple matter to implement each of these techniques as options in most VR systems. One disadvantage of these techniques can occur when the tailoring must be user-selected. Given that each technique defeats the purpose of some aspect of HMD technologies, it is unlikely that users will select these options on the basis of genuine preference. Moreover, novice users may not know the extent to which they are at risk for HMD-induced cybersickness. Given the rapid pace of technological change, the very definition of "novice user" is uncertain: Few studies have addressed the extent to which an individual's risk of cybersickness generalizes across platforms, applications, tasks, or other variables (cf. Sharples et al., 2008). There is no widely-accepted standard for the assessment of user experience or expertise. Assessments of user experience often are informal, non-standard, and unvalidated (e.g., Zielasko et al., 2019; Curry et al., 2020). Very few studies have utilized longitudinal methods that made it possible to evaluate experience-based changes (e.g., Bailenson and Yee, 2006).

In some approaches, tailored interventions are not user-selected, but are applied based on data collected from users, such as self-reports of symptom levels, or physiological data. A problem with these latter approaches is that the interventions can be applied only after the user has begun to experience cybersickness (e.g., Zielasko et al., 2018). It is for this reason that these techniques are referred to as *mitigation*.

2.2.2 Prevention through hardware re-design

2.2.2.1 Inter-pupillary distance

Stanney et al. (2020a), suggested that cybersickness in HMDs may be related to poor fit of the HMD headsets, in terms of inter-pupillary distance. They noted that existing headsets often cannot be set at an inter-pupillary distance that is appropriate for many female users. Because this issue affects women more than men, they suggested it might account for reported sex differences in cybersickness among HMD users. Limitations of their approach include the fact that its application is limited to HMDs, and can neither explain nor reduce sex differences in other areas of VR, such as desktop displays (e.g., Stoffregen et al., 2017). In addition, sex-specific postural precursors of cybersickness have been identified when postural activity was measured before users donned an HMD that induced sex differences in cybersickness (see Section 4.1.2). It is not clear whether the hypothesis of Stanney et al., 2020a, can explain such effects. More broadly, it remains to be seen whether reengineering of headset ergonomics can yield significant reduction in cybersickness.

2.2.2.2 Adding touch

Some researchers have attempted to relate optic flow to the user's sense of touch. Such interventions have been unrelated to motion parameters (e.g., airflow; D'Amour et al., 2017), or have attempted to synchronize optic flow with tactile vibration (e.g., Plouzeau et al., 2015; D'Amour et al., 2017). To date, neither of these approaches has yielded clear, consistent benefits. One problem with existing research is that it has focused on passive touch, rather than on active touch, or haptics, which differs qualitatively from passive touch and, in many cases, has been shown to enable far more accurate perception (e.g., Streit et al., 2007).

2.2.3 Summary

The techniques described in this section focus on aspects of the stimulus. That is, they focus on things that are made available for user perception. This approach tacitly accepts an implicit assumption that motion sickness is related in some way to sensory inputs (and hypothetical internal models of sensory inputs; Oman, 1982; Stoffregen and Riccio, 1991). It does not take into account any aspect of perceptual control, that is, how perceptual information is used by users to control behavior. In what follows, we argue that cybersickness interventions can and should be based on consideration of how it is that VR systems influence user behavior.

3 Theoretical and empirical foundations

Our recommendations for cybersickness interventions are developed from etiological theory and empirical research. Our work is motivated by the postural instability theory of motion sickness (Riccio and Stoffregen, 1991). The theory claims that motion sickness (including cybersickness) results from instabilities in the control of dynamic orientation of the head and body. That is, the theory claims that the subjective symptoms of motion sickness result from unstable postural control. This theory has its foundations in the Ecological Approach to Perception and Action (Gibson, 1966; Gibson, 1979), in which it is argued that the primary function of perception is the guidance of action. The Ecological Approach to Perception and Action asserts that perception is direct, that is, that sensory stimuli are sufficient, in and of themselves, for accurate perception. For this reason, the Ecological Approach rejects the common assumption that perception leads to the creation of mental models or estimates of physical reality. This rejection, in turn, raises questions about the widely accepted assumption that non-identities in the stimulation of different perceptual systems should be interpreted in terms of sensory conflict. Following from principles of the Ecological Approach, Riccio and Stoffregen (see also Stoffregen and Bardy, 2001; Stoffregen et al., 2017b) claimed that sensory conflict does not exist. That is, they rejected the assumption that non-identities in multi-sensory stimulation must (or should) be interpreted as being in conflict. In much of the VR community, the claims of the Ecological Approach to Perception and Action, and of the postural instability theory of motion sickness are heterodox, to say the least. Yet, the Ecological Approach to Perception and Action has proved to be highly influential in many domains, including display design (e.g., Burns and Hajdukiewicz, 2004), and the visual guidance of locomotion (e.g., Matthis et al., 2017; Serres and Ruffier, 2017). The postural instability theory of motion sickness has motivated a broad empirical literature that has illuminated novel facets of cybersickness. The postural instability theory is often cited in the VR literature; however, there have been few attempts to use the postural instability theory to motivate or develop methods for the prediction or prevention of cybersickness. A representative example is found in Lin et al. (2020), who cited the postural instability theory as an influential approach to understanding cybersickness, but motivated their research exclusively in terms of sensory conflict.

The foundation of our approach to cybersickness interventions is the empirical finding of postural precursors of motion sickness. The postural instability theory of motion sickness (Riccio and Stoffregen, 1991; Stoffregen, 2011) motivates monitoring of the quantitative kinematics of postural control (of the body, the head, and even of gaze) during (or before) exposure to potentially nauseogenic stimuli. The theory predicts that those quantitative kinematics will differ between individuals who (later) experience cybersickness, and those who do not, and that those differences will exist before the onset of subjective symptoms of motion sickness. Over more than 2 decades, this prediction has been confirmed in a wide variety of settings. The prediction has been confirmed in relation to movement during exposure (e.g., Merhi et al., 2007; Stoffregen et al., 2008; Dong et al., 2011; Curry et al., 2020a; Smart et al., 2020), but also in relation to movement before participants were exposed to any motion stimuli (e.g., Munafo et al., 2017; Curry et al., 2020b). In the context of cybersickness, the central prediction of the postural instability theory also has been confirmed in an increasingly wide range of independent laboratories (e.g., Cook et al., 2018; Weech et al., 2018; Risi and Palmisano, 2019; Teixeira and Palmisano, 2021).

Some empirical studies have questioned the validity of the postural instability theory. In the study of Dennison and D'Zmura (2017) participants wearing an HMD were exposed to visual rotation around the line of sight, while postural sway was recorded. The authors assumed that postural instability must necessarily consist of an increase in the spatial magnitude of movement. When they did not find that sway was greater among sick subjects, the authors concluded that the postural instability theory was not supported. However, Riccio and Stoffregen (1991) did not predict that motion sickness would be preceded by an increase in the spatial magnitude of sway. Rather, they predicted the postural sway would differ between participants with versus without motion sickness, and that these differences would exist before the onset of subjective symptoms of motion sickness. In fact, Dennison and D′Zmura found a statistically significant difference in sway between participants who became sick and those who did not (see their Figure 8)—a finding that is consistent with predictions made by the postural instability theory, as noted by Palmisano et al. (2018), and by Weech et al. (2018). Thus, ironically, rather than undermining the postural instability theory of motion sickness, the results reported by Dennison and D′Zmura actually support it.

The postural instability theory of motion sickness (Riccio and Stoffregen, 1991) can help us to understand the existence of individual differences in susceptibility to cybersickness. These differences relate to properties of the user, such as sex (e.g., Koslucher et al., 2016a), biomechanics (e.g., Stoffregen et al., 2010), and physical driving experience (e.g., Stoffregen et al., 2017a), as well as to properties of the task or situation in which users are engaged, such as controlling (vs not controlling) a virtual vehicle (e.g., Dong et al., 2011; Chang et al., 2021), or the physical movements used to control VR (e.g., Stoffregen et al., 2014). Aspects of VR technology are seen as being relevant to cybersickness to the extent that they (may) influence stabilization of the body.

It is important to note that the kinematics of human movement can be measured in a surprisingly wide variety of ways. In terms of dependent variables, the different types of assessment can be apportioned into two broad categories. This categorization is important because the two categories are orthogonal, in the sense that they can vary independently, and in the sense that—in different studies—postural precursors of motion sickness have been found in both categories, or in only one category. The first category comprises measures of the spatial dynamics of movement (in either linear or angular coordinates), such as the range of movement, or the standard deviation of body position, and time-derivatives of position, such as velocity, or frequency (e.g., Kim et al., 2018). A qualitative limitation of measures of spatial dynamics is that they do not permit analysis of the temporal structure of movement, that is, of temporal dynamics. Spatial dynamics differ qualitatively from movement dynamics. Measures of spatial dynamics provide information about the size or spatial extent of movement (e.g., "by how many centimeters do data points tend to differ from each other?"). Such magnitude measures tend, by their nature, to eliminate or discard the temporal structure of movement data, that is, how the measured quantity varies in time (e.g., "to what extent does movement at Time A resemble movement at Time B?"). The second category includes measures of the temporal dynamics of movement (e.g., Stoffregen et al., 2010). Techniques that assess only one of these categories may yield incomplete results, and can lead to erroneous conclusions about relations between cybersickness and human movement (e.g., Dennison and D′Zmura, 2017; Weech et al., 2018; Stanney et al., 2020b). Postural precursors of motion sickness have been identified in measures of spatial dynamics (e.g., Stoffregen and Smart, 1998; Dennison and D′Zmura, 2017), but have also been identified in numerous other measures of movement, including the temporal dynamics of movement (e.g., Stoffregen et al., 2010; Palmisano et al., 2018; Risi and Palmisano, 2019), the multifractality of movement (e.g., Munafo et al., 2017), the coupling of body movement with the dynamics of nauseogenic stimulus motion (Walter et al., 2019), and postural "time-to-contact", an intrinsic measure of stability that quantifies the instantaneous time remaining before body sway leads to a fall (Li et al., 2018). These empirical findings are important because they are consistent with the postural instability theory of motion sickness, but also because they can have implications for the design of cybersickness interventions, as will be discussed below. Riccio and Stoffregen (1991) suggested nine distinct measures of body movement that might yield postural precursors of motion sickness. Several of their suggestions have not yet been evaluated in empirical research; thus, the list of dependent variables in which postural precursors of motion sickness might exist is larger than the existing literature.

4 New options for cybersickness intervention

In this section, we discuss novel approaches to the development of cybersickness interventions that broadly fall into two categories. The first category focuses on the prediction of cybersickness in individual users. The second category focuses on the promotion of postural stability and, therefore, on the prevention of cybersickness.

4.1 Prediction of cybersickness in individuals

In this section, we argue that it is possible to predict the risk of cybersickness in individuals and that the identification of at-risk individuals can make important contributions to cybersickness interventions, and we offer novel methods for the identification of at-risk individuals. With respect to prediction, researchers typically have evaluated risk at the group level; that is in terms of the rates at which a given factor can be expected to induce cybersickness. Typically, prediction has been limited to estimates of the percentage of users that is likely to become sick, without any attempt to identify at-risk individuals (e.g., Arns and Cerney, 2005; Dennison et al., 2016; Chattha et al., 2020; Weech et al., 2020; Rebenitsch and Owen, 2021). This group approach can be helpful in evaluating technologies (e.g., in deciding whether to market a particular device), but cannot be used to tailor cybersickness interventions so that they apply only to individual users who need them. An alternative to prediction for groups is to predict the likelihood that cybersickness will occur in individuals; that is, to predict the risk of cybersickness for individual users or participants. If we can achieve reliable prediction of cybersickness for individual users, then we can warn those individuals that—if they continue—they are likely to become sick. No warnings would be needed for individuals who are not at risk; that is, warnings would be a tailored cybersickness intervention. We follow this latter strategy.

4.1.1 Prediction during exposure

Many researchers have proposed and/or attempted to develop methods that would permit the continuous (or, at least, frequent) monitoring of cybersickness status during exposure. Examples include subjective states, which can be reported frequently (e.g., the Fast Motion Sickness (FMS) scale; Keshavarz and Hecht, 2011, or presence), and physiological data, which can be monitored continuously (e.g., skin conductance; Dennison et al., 2016; Gavgani et al., 2017; Zielasko et al., 2017). Our approach differs qualitatively, in terms of the data on which we rely (postural kinematics), but also in terms of the goal that we seek. Existing proposals focus on early detection of cybersickness. In such cases, mitigation must focus on the suppression of existing symptoms or physiological indices. In other words, such interventions are reactive. Our approach focuses on the prediction of cybersickness among individuals who have not yet experienced any symptoms of cybersickness. It is for this reason that we refer to our approach as prediction, rather than as mitigation. Information about future cybersickness allows for the development of interventions that are proactive.

The postural instability theory of motion sickness predicts the existence of postural precursors of motion sickness; that is, patterns of postural activity that differ between individuals who will (later) become sick and those who will not. The most common method used to evaluate this prediction is to classify each participant as being either sick or well. Studies that have used this dichotomous method have yielded consistent results. Before the onset of subjective symptoms, postural precursors of motion sickness during exposure to visual motion stimuli have been identified in laboratory devices, (Stoffregen et al., 2010; Koslucher et al., 2014; Koslucher et al., 2016b), with projection video systems (Villard et al., 2008), with console video games (Dong et al., 2011), with tablet computers (Stoffregen et al., 2014), and in HMDs (Merhi et al., 2007; Curry et al., 2020b). The nature of these postural precursors differs between the sexes (e.g., Koslucher et al., 2016b; Curry et al., 2020b), between people who control the VR and people who are passive observers (e.g., Dong et al., 2011), and between different measures of postural kinematics, including spatial and temporal measures (e.g., Villard et al., 2008). The general effect is well-established, but additional research will be needed to identify the parameters and dependent variables that will yield optimal prediction algorithms.

The robust existence of postural precursors of motion sickness makes it possible, in principle, to use data on postural kinematics to identify individual users who are at risk for cybersickness. A relatively simple application of this information would be to use it to trigger warnings for individuals (e.g., "If you continue, you may experience cybersickness"); warnings that would appear only for those individuals who were identified as being likely to become sick in the current VE setting. The exact values of movement parameters that trigger warnings can be determined empirically, or adjusted for different applications (e.g., business vs. gaming). With pattern recognizing AI, it would be possible to build a database across users that would automatically improve prediction. A disadvantage of warnings is that they defeat the purpose of the technology, in the sense that at-risk users may choose simply to stop using it.

Some studies have examined the quantitative kinematics of posture in the context of cybersickness but, for methodological reasons, cannot be used to refine our ability to use postural data to predict cybersickness in individuals. As one example, Chardonnet et al. (2015) recorded standing body sway among participants who were exposed to VE. Their results revealed that the spatial magnitude and frequency structure of sway changed over time during exposure, and varied in relation to the duration of exposure (before sickness onset). Unfortunately, each participant was exposed until they became sick, and for this reason the results cannot be used to differentiate between individuals who were *versus* were not at risk for cybersickness.

Weech et al. (2018) assessed several variables before participants were exposed to potentially nauseogenic VR presented through an HMD. The authors attempted to predict post-exposure cybersickness data from their battery of pre-exposure assessments. Using principal components analysis, they found that the strongest predictor of post-exposure cybersickness was pre-exposure postural sway. In addition, they found no evidence that prediction was improved by the addition of non-postural measures of vection strength and vestibular sensitivity. We claim that, during exposure, postural kinematics are sufficient to evaluate the risk of cybersickness in individuals. To some extent, our claim is a promisory note: Additional research is needed to fine-tune existing prediction techniques (e.g., Smart et al., 2002; Weech et al., 2018).

4.1.2 Prediction before exposure

It has sometimes been claimed that postural instability does not cause motion sickness but, rather, that sensory conflict simultaneously causes both motion sickness and unstable control of posture (e.g., Akiduki et al., 2003; Akizuki et al., 2005; Nishiike et al., 2013; Fulvio et al., 2021). Similarly, some researchers have attempted to use postural data as a direct measure of the magnitude of sickness (e.g., Kim et al., 2018). These claims have not acknowledged or taken into account the common finding that postural precursors of motion sickness exist before exposure to nauseogenic stimuli (e.g., Stoffregen and Smart, 1998; Koslucher et al., 2016a; Munafo et al., 2017; Palmisano et al., 2018; Arcioni et al., 2019; Curry et al., 2020a). In some studies, researchers have measured postural kinematics before participants were exposed to potentially nauseogenic motion stimuli but did not use these data to test the hypothesis that pre-exposure postural activity might differ between participants who later reported motion sickness and those who did not (e.g., Akiduki et al., 2003; Nishiike et al., 2013; Chardonnet et al., 2015).

The finding that there are postural precursors of motion sickness before exposure to motion stimuli raises the possibility that individual susceptibility to cybersickness might be determined before exposure to VR applications. With HMDs, prediction before exposure might be achieved using head movement data collected after the headset is donned but before the onset of virtual locomotion. For example, while logging in, selecting apps and settings, or while reading a disclaimer, instructions, or other text. The essential requirement is that movement data would be collected before participants were exposed to any moving stimuli.

A major practical advantage of our approach is the extent to which it is non-invasive. Once an intervention has been developed, validated, and implemented, participants should not need to answer questions, engage in specific, directed movements, or even be aware that their movements are being monitored. In terms of user experience, our approach contrasts with other approaches in which participants are required to devote deliberate attention to the provision of subjective reports. Examples include the FMS (Keshavarz and Hecht, 2011) and any other sequential rating of symptoms. That being said, when user experience is not a priority, our approach can be combined with the collection of subjective ratings.

A growing literature reports efforts to predict cybersickness using a variety of advanced modeling techniques, including structural equation modeling (e.g., Venkatakrishnan et al., 2020), machine learning (e.g., Dennison et al., 2019), and deep learning (e.g., Liao et al., 2020). We recognize these mathematical techniques as having potential value for the prediction of cybersickness in individuals. Our caveat concerns the nature of the data on which such mathematical models operate. In the existing literature, few modelling efforts have included any data on quantitative postural kinematics. Rare exceptions have used only measures of the spatial dynamics of movement (e.g., Jin et al., 2018). We claim that algorithmic prediction of cybersickness in individuals will be most successful when it is grounded on data on the quantitative kinematics of postural activity (cf. Weech et al., 2018). One open issue concerns the nature of unstable movement that precedes cybersickness. As noted above, postural precursors of motion sickness have been identified in different measures of movement kinematics, many of which are orthogonal to one another (e.g., measures of the spatial vs temporal dynamics of movement). It remains to be seen whether there is a movement parameter that is the "one best" predictor of cybersickness, or whether different variables will be optimal for different situations (e.g., cybersickness in HMDs vs desktop systems).

4.2 Prevention of cybersickness during VR use

Prediction is useful, but it is only half the battle. If the prediction of cybersickness is used only to prevent individuals from using VR systems, then surely the purpose of VR systems is being defeated: We want more people to be able to use VR, not fewer. Greater value may be found in prevention. The prevention of cybersickness often has been viewed as a matter of technology design, relating to technological development: Higher spatial resolution, higher temporal resolution, faster processing and updating, and so on. As noted in an earlier section, this approach has not been successful.

Other efforts to prevent motion sickness do not take into account the predictive power of postural kinematics, and have not been designed to increase the stability of bodily control (e.g., Zielasko et al., 2018). Possibly for this reason, the interventions evaluated by Zielasko et al. did not yield any statistically significant benefits. The idea of modulating VR to prevent sickness may not be new, but the idea of modulating VR to stabilize posture (thereby preventing sickness) is new. Our novel idea is to use real-time data on postural kinematics to adjust VR dynamics in ways that will stabilize posture, thereby yielding significant improvement in the prevention of cybersickness.

Preventive strategies derived from our approach can differ dramatically from traditional strategies. As two very simple examples, statistically significant reductions in the incidence of visually induced motion sickness can be achieved through the simple expedient of adopting a wider stance (Stoffregen et al., 2010), or sitting down (Stoffregen et al., 2008). Each of these interventions has the effect of increasing the stability of the body. In this section, we focus on changes in the design of interactive VR systems that may promote stable control of the body. We believe it is possible to design VR systems (both hardware and software) in ways that tend to support or facilitate postural stability. Increased bodily stability should lead to reduced cybersickness. We believe that these types of interventions can be developed and implemented in ways that are either inconspicuous or entirely invisible to users. Accordingly, such interventions should lead to greater user acceptance and satisfaction (relative to, for example, FOV restriction).

The central idea in our approach is to take advantage of the fact that HMD units collect real-time data on the quantitative kinematics of user movement. These real-time data can be used to identify users who are becoming unstable, and to modify system dynamics to promote stability, thereby reducing cybersickness, or preventing it altogether. Our approach constitutes a novel challenge for system designers. The challenge is not random, given its basis in a large body of both theoretical and empirical research. In addition, the challenge is well within the capabilities of existing technologies. The challenge is not to create new technologies but, rather, to use existing technologies in novel ways. In the remainder of this section, we describe some novel cybersickness interventions that follow from our theoretical perspective and empirical research.

4.2.1 Motion frequencies

A considerable body of research shows that motion sickness is associated with imposed motion in a narrow range of frequencies (Riccio and Stoffregen, 1991). By contrast, little is known about the stimulus for sickness when the motion stimulus is under the user's control (e.g., for drivers, rather than passengers). Nevertheless, it seems likely that frequency will play a role in the genesis of motion sickness even with self-controlled movement. With HMDs, it is easy to monitor user movement in terms of frequency, and it is possible to extract (from in-game data) the frequencies of visual display motion. For individuals who are identified as being at risk of cybersickness (based on data on bodily movement), VR system dynamics could be modified in real-time to implement a band-block filter that would remove visual motion in the risky frequency range. New research would be required to develop the necessary analytic and software tools, and to evaluate possible effects such interventions on postural stability, and on cybersickness. It might be argued that a band-block filter would reduce the fidelity of the VR. In a literal sense, this is true. However, deliberate (i.e., designed) modification of the oscillation frequencies of interactive systems is a common feature of daily life. Perhaps the most widely experienced example is suspension systems on automobiles. Engineers deliberately design automobile suspension systems so that they do not transmit (from the ground to vehicle occupants) certain characteristics of the road surface. That is, the suspension system works to "smooth out the bumps". In some technical sense, this smoothing reduces the "fidelity" of vehicle ride, but this is a desirable feature—it is exactly what the suspension system is intended to do. Our suggestion with respect to a band-block filter for VE motions follows the same logic, but applies that logic only to individual users who can most benefit from it.

4.2.2 Earth referents and postural stability

As noted in Section 2.2.1.3, there exists considerable confusion over the concept of rest frames. In part, this confusion arises from issues in classical theories of perception. In these views, visible referents are important because they are compared to internal models of the physical world (e.g., Prothero and Parker, 2003). However, alternative theories of perception exist, which do not rely on the existence of hypothetical internal models. Another difficulty, in our view, is that common conceptualizations of rest frames do not relate to perception-action coupling. Rather than comparing visible features of the environment to internal models, perception of the user's orientation may be used (in part) to stabilize the body. In fact, motion of the visible environment relative to the body can have effects on the control of posture that are profound (e.g., photons can knock you down; Lee and Aronson, 1974; Stoffregen et al., 1987). Many studies demonstrate that body sway becomes "coupled" to oscillatory motion of the visible environment (e.g., Lee and Lishman, 1975; Stoffregen, 1985). Of critical importance is the fact that these effects exist even when visual motion is so subtle that participants are not aware of it, and do not experience vection.

Whenever we are awake and not lying down, postural control is continuous. This includes the stabilization of the entire body, in stance, but also the stabilization of the head and torso (e.g., when sitting on a stool), and the stabilization of the head (e.g., when leaning against the back of a chair). As a matter of physics, the body must be stabilized relative to the forces acting upon it, which are referred to collectively as the gravitoinertial force vector (e.g., Stoffregen and Riccio, 1988). Perceptual information is used to monitor dynamic stability, and to organize adaptive control actions—applications of force to the ground that maintain the body's center of mass over the base of support. This activity is complex, relying on multisensory information, but most of the time the maintenance of stability goes on without conscious of awareness—life would be very tedious if we were constantly aware of the subtle details of bodily stability.

The need to control the body relative to the gravitoinertial force vector can help to reorient our understanding of the functional role of visible referents. A robust example can be found in life at sea. For millennia, folk wisdom has held that bodily stability can be improved, and seasickness avoided, by spending time on the open deck of a ship, looking at the Earth horizon (Stevens and Parsons, 2002). Recent research has revealed that these anecdotal reports have a foundation in the fine details of bodily control and stabilization. While standing on the deck of a ship at sea, postural sway while looking at the horizon is more stable than when the same person, standing in the same place on the same ship, looks at some nearby target, such as a railing, or deck chair (Mayo et al., 2011; Stoffregen et al., 2013). Stoffregen et al. (2013) measured standing postural sway before the beginning of a sea voyage, and competed these data to reports of seasickness during the voyage. They found that pre-voyage postural sway differed between participants who later reported seasickness and those who did not.

We predict that similar effects can be engineered into VR systems. Rather than focusing on "rest frames" that are head-fixed and task independent (e.g., Wienrich et al., 2018), we recommend that virtual environments be designed to include what we call Earth referents: These are elements of VR displays that are stable relative to the Earth, that is, the real, physical Earth on which the user physically sits or stands. Some studies indicate beneficial effects for Earth referents that are in the visible background (Duh et al., 2001; Stoffregen et al., 2013). However, a large body of research has shown that, on land, postural stability can be optimized by Earth referents that are visually nearby (e.g., Stoffregen et al., 2000; Munafo et al., 2016a). Such findings are related to the fact that postural stabilization is not limited to alignment relative to the gravitoinertial force vector. Simultaneously, we typically stabilize ourselves relative to task-related aspects of the environment, such as text, or other objects of regard. In this context, postural precursors of motion sickness may exist in the kinematics of gaze (cf. Stoffregen et al., 2006a), a prediction of the postural instability theory that has yet to be tested empirically.

Considerable research will be needed to determine the optimal use of Earth referents in VR systems. Such research should focus on the effects of visible display elements (e.g., their apparent stasis relative to different physical referents) on the physical stabilization of the body. This latter aspect is critical: As indicated by the basic science research cited in the previous paragraph, the central criterion is the physical stability of the body, rather than vection, presence, or other aspects of subjective experience.

The use of Earth referents could be tailored to individual needs. For example, Earth referents might be added to the VR experience when an individual user began to show signs of postural instability. That is, when the system detects that an individual was at risk for cybersickness, the VR display could be modified, online and in real-time, to include nearby Earth referents. In principle, such referents might be added in ways so that they stabilize posture without impacting on users' subjective experience (cf. Lee and Lishman, 1975; Stoffregen, 1985).

4.2.3 Sex differences

Both anecdotal reports (e.g., Boyd, 2014) and controlled research indicate that cybersickness often differs between the sexes, with women more likely than men to become sick. Traditional analyses of this issue have focused on potential perceptual or cognitive differences between the sexes (e.g., Fulvio et al., 2021), or on the idea that reported sex differences may be an artifact of the ergonomics of headsets (e.g., Grassini and Laumann, 2020; Stanney et al., 2020a). By qualitative contrast, the existence of sex-specific postural precursors of cybersickness (e.g., Koslucher et al., 2016a; Koslucher et al., 2016b; Munafo et al., 2017; Curry et al., 2020a; Curry et al., 2020b) confirms the physical reality of sex differences in cybersickness, and opens new avenues for cybersickness interventions that are targeted at this problem. Our focus on cybersickness interventions that are tailored to individual users will naturally take into account the existence of sex-specific postural precursors of motion sickness. The existence of sex-specific patterns of postural activity means that it should be possible for this tailoring to be achieved without intentional user input; that is, algorithms may detect sex from postural kinematics, without the need to self-report sex. Under our approach, cybersickness interventions would tend to be applied to women more often than to men, such that the benefits would tend to accrue to women more than to men. In this way, our approach can lead to an overall reduction in the extent to which HMD systems are sexist in their effects.

5 Discussion

In this article, we have not attempted to provide detailed suggestions for cybersickness interventions that could readily be implemented. Such detailed suggestions can be developed only from additional research. Our primary motivation is to explain the new approach in sufficient detail that readers can see how it differs from previous approaches, can understand that additional research is needed, and can appreciate that it may be worthwhile to conduct such research. Much of the needed research can be done using existing technology, and with modest effort. This is so especially with HMD systems, which necessarily collect data on the detailed kinematics of the user. It is a relatively simple matter to use those "naturally occurring" data on movement kinematics to provide answers to many of the questions that are motivated under our approach and, thereby, to provide the empirical foundation that will be essential to the implantation of cybersickness interventions derived from our approach. In our approach, there is no motivation or need for special purpose devices, such as wearable sensors for galvanic skin response, heart rate, stomach motility, and so on (e.g., Weech et al., 2020).

5.1 Theory and the design of research

The postural instability theory differs from other theories of motion sickness in many respects (Riccio and Stoffregen, 1991). It motivates different testable hypotheses, different experimental designs, different dependent variables, and different types of data analysis. The resulting research has revealed new phenomena and new effects; in many cases, effects that were not predicted by and have not (yet) been explained in terms of any version of the sensory conflict theory (e.g., Stanney et al., 2020). Researchers have sometimes argued that particular empirical studies have contradicted predictions made by the postural instability theory. However, as noted at several points in this article, the conclusions derived from those studies are not justified by the design, the data, and/or the data analyses. In general, the collection of data on postural kinematics is not, by itself, sufficient for researchers to reach conclusions about the existence or nature of postural precursors of motion sickness. It is necessary also that research be designed so as to permit testing of the relevant hypotheses.

A core requirement of future research will be to distinguish commonalities in movement kinematics that may be related to characteristic phenomena of cybersickness. Interactive technologies vary in many ways. Examples include the weight and weight distribution of headsets, and the field of view, or depth of field of displays. Similarly, there are wide variations in the tasks undertaken by users of interactive technologies. Examples include active *versus* passive control (e.g., Dong et al., 2011; Chang et al., 2021), locomotion *versus* stationary rotation (e.g., Munafo et al., 2017), or fixating *versus* tracking. Similarly, people use interactive systems while assuming different postures, such as sitting *versus* standing (e.g., Merhi et al., 2007). How do such variations influence the kinematics of user movement, and how are these changes related to individual and group variations in cybersickness?

Additional research also will be needed to better understand the quantitative details of postural precursors of motion sickness. Is cybersickness more strongly predicted by measures of the spatial dynamics of movement (e.g., position, and its time-derivatives; Stoffregen and Smart, 1998), by the temporal dynamics of movement (e.g., self-similarity; Stoffregen et al., 2010), by the fractality of movement (e.g., Munafo et al., 2017), or in intrinsic measures of stability, such as postural time-to-contact (Li et al., 2018)? Is there a measure of postural kinematics that is the “one best” predictor of cybersickness, or do postural precursors vary across technologies, postures, applications, tasks, and/or user groups?

5.2 Predictive algorithms

As we noted in Section 4.1.2, current application of computational algorithms to the prediction of cybersickness has focused on types of data that have a weak track record and (from our perspective) are not likely to yield results that are effective. We agree that computational algorithms can be used to predict cybersickness (e.g., Smart et al., 2002; Smart et al., 2021). However, in developing computational algorithms, we recommend that researchers focus on the sorts of variations that have been shown to affect postural precursors of cybersickness. As noted in Section 4.2.3, postural sway differs between women and men, and research inspired by this fact has revealed that postural precursors of cybersickness differ between women and men. Another example concerns biomechanical aspects of stance: Variations in stance width (i.e., the distance between the feet) can powerfully affect the kinematics of body sway (e.g., Mouzat et al., 2004), and are known to influence postural precursors of motion sickness (Stoffregen et al., 2010). Finally, many factors influence the functional integration of postural control with suprapostural activity; that is, the things we do while we are sitting or standing (e.g., Riley et al., 1999; Balasubramaniam et al., 2000; Stoffregen et al., 2000; tasks, such as reading a tex). Such factors have also been found to influence postural precursors of cybersickness. Several studies have found that cybersickness is preceded by different patterns of postural activity for participants who have been engaged in different tasks, such as reading a text *versus* looking at a blank page (e.g., Koslucher et al., 2016a; Munafo et al., 2017; Curry et al., 2020a). Research of this kind suggests new avenues for the development of algorithms for the prediction of cybersickness. In the end, the success of such algorithms may have less to do with particular computational techniques than with the nature of the data on which they operate.

5.3 Postural precursors of cybersickness: Uniqueness and commonality

Recent research has raised the possibility that the detailed kinematics of postural activity may be unique to each individual, suggesting that each of us may have a “movement fingerprint” (Slowinski et al., 2016). The existence of unique, individual movement fingerprints would raise the possibility that online analysis of headset-sensed movement could be analyzed in real-time to detect unique, individual postural precursors of motion sickness, permitting truly individual tailoring of preventive interventions. The existence of unique, individual patterns of movement also would contribute to the development of prevention techniques that are invisible. It might seem, then, that postural precursors of cybersickness must also be unique to each individual, such that it would be necessary to make each person sick so as to identify their unique postural precursors of cybersickness. We are not so pessimistic. There are individual differences in every aspect of humanity, yet there also are powerful commonalities. Indeed, while each fingerprint is unique, it also is true that fingerprints resemble each other. As one example, fingerprints are classified into different types, such as loops, curves, arches, and whorls (e.g., Maltoni et al., 2009). Similarly, while it may be that everyone's postural sway is unique, postural kinematics exhibit generalized characteristics (e.g., oscillations in the range 0.1–0.4 Hz). Just as fingerprints can be classified using machine learning and other computation algorithms (e.g., Win et al., 2020), it may be possible to use similar computational approaches to classify the kinematics of movement to reveal individualized susceptibility to cybersickness.

5.4 Cybersickness in research, but not in implementation

We claim that our approach can lead to the development of interventions that will prevent cybersickness, and that these can be tailored to those who need them, while remaining invisible to other users. It will be necessary to induce sickness as part of conducting research that can guide the development of such interventions. But the final, fully implemented interventions should not depend upon the induction of sickness in actual users. In particular, it should not be necessary to make a person sick so as to know what kinematic patterns predict cybersickness in that individual. In large part, this should be so due to the existence of both uniqueness and commonalities in the kinematics of movement (Section 5.3). A critical aim of future research should be to distinguish, empirically, between aspects of individual uniqueness in movement that must be taken into account in predicting cybersickness, in relation to commonalities of human movement that may be sufficient for the prediction of cybersickness.

6 Conclusion

Our approach to cybersickness emerges from the Ecological Approach to Perception and Action, a general theory of behavior that rejects the traditional focus on hypothetical information processing in favor of a focus on perception and control in the animal-environment system (e.g., Gibson, 1966; Gibson, 1979; Stoffregen and Bardy, 2001). Our approach offers new possibilities for the prediction of cybersickness in individuals. We have argued that such interventions can improve the prediction of cybersickness in individuals while remaining invisible to users. Yet the larger prize, we believe, is the possibility to combine improved prediction with online, real-time modifications in system dynamics that can stabilize posture and, thereby prevent cybersickness. Prevention has the potential to increase the universe of VR users (i.e., by making use possible for more people).

Approaches to the problem of cybersickness that rely on the tailoring of interventions to individual users necessarily have at least one important limitation: Such approaches may not be applicable to situations in which standardization is required, for example, when it is mandatory that all users be exposed to precisely the same stimuli. This limitation applies to our approach and to any other that attempts to predict, prevent, or mitigate cybersickness in individuals (e.g., Zielasko et al., 2017; Zielasko et al., 2018).

Our approach offers new options to predict cybersickness, but also to prevent it. In the present article, we have presented only a few novel options, but our approach, comprising the postural instability theory of motion sickness and its superordinate more general theories of perception-action and human-machine systems, can inspire a wide variety of new strategies for cybersickness interventions. Our approach offers new ways to deal with the problem of sex differences in cybersickness and, in so doing, can make the technology more inclusive, yielding more users, but also reducing or ending sex discrimination.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

GB conceived, wrote, and revised the manuscript. TS conceived, wrote, and revised the manuscript. DA revised the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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