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Evaluating VR Sickness in VR Locomotion Techniques

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ABSTRACT
VR Sickness is a form of motion sickness in Virtual Reality that affects 25–60% of the population. It is typically caused by exposure to mismatches between real and virtual motion, which happens in most VR Locomotion techniques. Hence, VR Locomotion and VR Sickness are intimately related, but this relationship is not reflected in the state of VR Sickness assessment. In this work we highlight the importance of understanding and quantifying VR Sickness in VR locomotion research. We discuss the most important factors and measures of VR to develop VR Sickness as a meaningful metric for VR Locomotion.

1 INTRODUCTION
VR Sickness† and VR Locomotion are intimately related: VR Sickness is typically caused by some form of mismatch between perceived and expected motion patterns [2, 21, 23, 24] and VR Locomotion enables a user to move around in an immersive Virtual Environment (VE) that can be infinitely much larger than the physical space the user is confined to. This means that, by the very nature of the topic, VR Locomotion often involves mismatches between physical and virtual motion. Current VR Locomotion research is often limited in how they assess VR Sickness in three ways: 1) many measures of VR Sickness do not measure VR Sickness or only do so in a limited way; 2) the design of locomotion techniques and their experimental evaluation insufficiently consider the factors related to VR Sickness; and 3) the data produced by the experiments are often inadequately reported.

Picking the right tool to measure VR Sickness is difficult. Currently, the most common measure employed in VR Locomotion research is the Simulator Sickness Questionnaire. However, VR Sickness differs from other forms of motion sickness, including Simulator Sickness, in that it typically exhibits disorientation, dizziness, eye strain and vertigo symptoms instead of nausea [18, 25, 26, 30]. Unfortunately, while a few alternative questionnaires exist they have their own drawbacks and much is unclear about their use and validity. On top of that, the symptoms of VR Sickness as well as their severity can differ wildly between different people; Some users may feel nauseated instantly while others only develop (different) symptoms after prolonged exposure or do not feel affected at all. Despite decades of research on motion sickness it is still not clear how these differences can be explained.

Several factors in software, demographics and hardware have been identified that may influence one’s susceptibility to VR Sickness [1, 5, 24, 26]. The design of a VR Locomotion technique should always consider the possible VR Sickness risks and in evaluating the technique it should be made clear what aspects need improvement. New types of locomotion techniques provide another challenge: recent advances in VR hardware include new tracking and display systems have enabled new ways of interacting with an immersive VE. For example, non-isometric walking has recently been proposed as a locomotion technique [11, 33, 35] with the promise of naturalistic movement with a large range of motion, but it is still unclear how this type of movement affects VR Sickness.

Works on VR Locomotion often provide inadequate reporting of relevant factors such as exposure to optical flow and participant backgrounds, or provide incomplete data on the results of a VR Sickness measure. In particular, several of the confirmed demographic factors are rarely reported (discussed in Sect. 3) and sickness questionnaire responses are rarely reported in enough detail to draw meaningful conclusions on whether and how a locomotion technique might cause VR Sickness. Ideally, a VR Locomotion paper would provide enough detail to characterize the type of movement in some way and correlate it with the observed VR Sickness response. Currently, it is difficult to learn more about VR Sickness from a VR Locomotion paper and vice-versa.

Together, these issues make assessing VR Sickness in locomotion techniques particularly challenging. Not only that, but given the relationship between VR Locomotion and VR Sickness it seems obvious that results from either area should be able to inform the other, but this is currently near-impossible. In this work we provide a short overview of current VR Sickness measures and their shortcomings, as well as the most relevant factors in software and demographics that need to be considered in both the design and evaluation of VR Locomotion techniques. Finally, we discuss what an ideal scenario of VR Sickness evaluation would look like and provide some suggestions for immediate improvement.

2 MEASURING VR SICKNESS
The Simulator Sickness Questionnaire (SSQ) [15] is the most common measure that is used to evaluate VR Sickness responses for VR Locomotion techniques. The SSQ produces a Nausea, Oculomotor, Disorientation and Total Severity score that together indicate a level of "Simulator Sickness". While widely used, the SSQ has some important shortcomings: the SSQ measures Simulator Sickness instead of VR Sickness, it was designed for a military demographic, and it has issues w.r.t. length, interpretation and overlapping factors [4, 26, 28]. Furthermore, several works that employ the SSQ fail to adequately report on, for example, the N, O, and D scores or fail to mention whether the questionnaire was administered before as well as after the task. To overcome the problems of the SSQ two derivative questionnaires have recently been developed: the Virtual Reality Sickness Questionnaire (VRSQ) [18] and the Cybersickness Questionnaire [32]. A recent study by Sevinc and Berkman [28] found that the SSQ is not an appropriate measure for modern HMD VR applications, while the VRSQ and CSQ are valid and reliable measures although they suffer from small sample sizes.

Other approaches to measuring VR Sickness include the Fast Motion Sickness Scale (FMS) [16] or the Misery Scale [3] as well as countless variations of a single question asking the participants to rate their level of "sickness". These single-question style approaches allow for fast approximation of a user’s comfort level while not breaking presence and allowing rapid measurements. Unfortunately the results are hard to interpret and compare since it is unclear to what degree these scales actually measure VR Sickness. Furthermore, participants may not interpret the symptom the same way, which may also happen for similar-style questions on Vection (illu-

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† Also known as “Cybersickness” or “Visually-Induced Motion Sickness” (VIMS). There is some debate on the similarity between these forms of motion sickness.
sory self-motion). Vection may be beneficial for VR Locomotion, and Vection and VR Sickness often appear around the same time. Most of this relationship is still unclear however, although they are likely not responsible for causing each other [8, 17, 20].

An interesting way of measuring VR Sickness comes from the Ecological Theory of Motion Sickness [27, 31]: the theory is based around the idea that the human body always tries to maintain balance. When this process is disturbed by external forces (such as illusory visual motion) postural instability ensues, and prolonged exposure to postural instability then leads to motion sickness symptoms. This postural instability can be measured objectively and has been correlated with VR Sickness responses: increased postural instability can act as both a predictor and indicator of VR Sickness in a user [6, 7, 22, 26, 29, 34]. Similarly, gait [12, 33] and physiological measures [7, 13, 19] have been used as objective measures of VR Sickness.

3 VR Sickness factors
It is important to consider the factors that may influence VR Sickness throughout the design and evaluation of a VR locomotion technique. Several aspects of the user, the software/task and hardware have been confirmed to influence VR Sickness but they are rarely discussed in VR Locomotion papers. It is infeasible to go over all the possible factors and the research related to them here, but thankfully we have several reviews that collect the state-of-the-art of VR Sickness (cybersickness) factors such as the work done by Rebenitsch and Owen [26] as well as others [1, 5, 9, 21, 24]. In this section we will provide a short summary of some factors that are especially relevant for VR Locomotion as discussed in the mentioned reviews.

Demographics factors relate to an individual’s susceptibility to VR Sickness and may be used to estimate whether a certain technique is safe for certain demographics. One of the main factors that has been correlated with VR Sickness is History of Motion Sickness: people who get motion sickness typically also suffer from VR Sickness. Some questionnaires to record this exist (e.g. [10, 24]). Furthermore, increased Experience with VR and video games, as well as higher Age, lowers VR Sickness risk. A history of Migraines also increases VR Sickness risk and there seem to be Gender differences. Some works have shown that people and different genders have different postural instability patterns pre-exposure and that increased pre-exposure postural instability predicts higher VR Sickness incidence.

Duration and Optical Flow are two key software/task factors. VR Sickness is correlated with duration (time spent in the sickness-inducing environment) and may be accumulative even after several days. A recent model by Rebenitsch and Owen [25] predicts measurable VR Sickness levels (SSQ scores) after a duration of 15 minutes. This is problematic because a typical trial in a user study is much shorter than this and may thus not show VR Sickness effects. On the other hand, practice or experience can mitigate VR Sickness, and some users are already affected after mere seconds of exposure. Optical flow is the perceived motion of light patterns and is as such closely related to the relative movement between the avatar and the virtual world. Optical flow may increase the risk of VR Sickness and some works suggest that this happens for a particular motion frequency, although the exact range is unclear. Furthermore, rotational motion typically causes stronger sickness effects than translational motion, but especially with regards to Level-of-Control and body-based 6-DoF movement much remains unknown.

If anything, recent works on VR Sickness factors highlight a lack of coverage even for well-known factors such as duration, and especially for modern systems. VR Locomotion can help remedy this by explicitly considering these factors in their works. Finally, hardware factors such as refresh rate, display flicker, input lag and field-of-view have all been correlated with increased VR Sickness incidence. Modern hardware has alleviated some hardware-related causes, although at the same time it has introduced new questions such as how body-based 6-DoF locomotion affects VR Sickness. Furthermore, improving some factors, such as field-of-view or realism, may not only improve Presence but also increase VR Sickness incidence.

4 VR Sickness evaluation we wish to achieve
In an ideal world, a paper presenting a locomotion technique for VR would include a thorough assessment of the risk of that technique causing VR Sickness. Not only would this facilitate adoption of the locomotion technique and future improvements, it would also improve our understanding of VR Sickness. In this world, VR researchers would have access to an agreed-upon set of guidelines for conducting locomotion experiments with respect to VR Sickness evaluation. Future techniques, like fully online assessment of sickness levels, would be very beneficial to determining what combination of factors and motion causes VR Sickness. Of course, in a perfect world VR Sickness would be a thing of the past entirely, but to get to that point more research is needed today.

Achieving this is hampered by the limited tools and knowledge we have on VR Sickness at the moment. VR Sickness is a complex phenomenon that despite decades of research on motion sickness remains intangible. It is understandable that many recent VR Locomotion works do not report VR Sickness measures to a meaningful degree; truly measuring VR Sickness may remain a task for Motion Sickness research. More work is needed to determine how modern VR systems, comprising advanced tracking systems and software, influence VR Sickness. Much of the motion sickness research is dated and recent techniques (e.g. with magical properties or body-based room-scale tracking) have not yet been thoroughly investigated. Some attempts at creating models of VR Sickness have been made (e.g. [25]) and Postural Instability measures are promising, but more work is needed in this area as well. Machine Learning approaches (e.g. [13, 14]) may help us in further assessing the VR Sickness incidence for a particular application, but due to the lack of fundamental knowledge on VR Sickness their usefulness will likely remain limited for now.

5 Final thoughts
Today, there is much to be gained in terms of evaluating VR Locomotion techniques in a meaningful way to allow us to compare and improve different techniques. For example, the recently developed VRSQ or CSQ questionnaire may be more appropriate than the SSQ despite the apparent usefulness of being able to compare SSQ scores. Better reporting of participant characteristics, such as their history of motion sickness, may take us a long way towards better understanding VR Sickness results for a given technique. Separating the participants into a “susceptible” and “non-susceptible” group may provide additional insights. Finally, more work is needed on the effect of exposure duration on VR Sickness incidence so that we may design better experiments.

The VR research community needs discuss how to practically assess VR Sickness in VR Locomotion research in a way that not only allows us to evaluate locomotion techniques based on their VR Sickness effects, but that also informs VR Sickness research by providing valuable data. To this end, a better understanding of VR Sickness and better reporting of VR Sickness measures are crucial.

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