The Effects of Secondary Task Demands on Cybersickness in Active Exploration Virtual Reality Experiences

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Abstract—Active exploration in virtual reality (VR) involves users navigating immersive virtual environments, going from one place to another. While navigating, users often engage in secondary tasks that require attentional resources, as in the case of distracted driving. Inspired by research generally studying the effects of task demands on cybersickness (CS), we investigated how the attentional demands specifically associated with secondary tasks performed during exploration affect CS. Downstream of this, we studied how increased attentional demands from secondary tasks affect spatial memory and navigational performance. We discuss the results of a multi-factorial between-subjects study, manipulating a secondary task's demand across two levels and studying its effects on CS in two different sickness-inducing levels of an exploration experience. The secondary task's demand was manipulated by parametrically varying n in an aural n-back working memory task and the provocativeness of the experience was manipulated by varying how frequently users experienced a yaw-rotational reorientation effect during the exploration. Results revealed that increases in the secondary task's demand increased sickness levels, also resulting in a higher temporal onset rate, especially when the experience was not already highly sickening. Increased attentional demand from the secondary task also vitiated navigational performance and spatial memory. Overall, increased demands from secondary tasks performed during navigation produce deleterious effects on the VR experience.

Index Terms—Virtual Reality, Cybersickness, Secondary Task Demand, Active Exploration, Electrodermal Activity

1 Introduction

Virtual reality (VR) technology is increasingly being applied to areas like gaming [16], training [22], therapy [86], education [83], sports [86], etc. Despite this growing popularity, VR is yet to become a ubiquitous computing platform that we, as humans, default to. This failure to see widespread adoption can largely be attributed to the manifestation of cybersickness (CS), an affliction analogous to motion sickness (MS), which accompanies VR experiences as an undesirable side effect, inhibiting the technology's sustained usage [44, 84]. Cybersickness strongly occurs in virtual experiences that involve virtual motion as users perceive motion through visual stimulation (vection) in the absence of real body motion [35]. The affliction is hence commonly called visually induced motion sickness (VIMS), exhibiting similar undesirable symptomatological effects like dizziness, disorientation, nausea, fatigue, eye strain, etc., [35, 41]. Modern VR applications often feature expansive immersive virtual environments (IVEs) that users explore by virtually traveling, increasing the potential for CS to manifest. This makes it essential to study factors associated with the affliction, in attempting to combat the deleterious effects it produces.

In active exploration experiences, users are afforded control over their motion to virtually navigate through an environment, going from one place to another [79, 84]. These kinds of experiences generally involve users primarily engaging in navigation, an overall task that consists of the components of travel and wayfinding [5]. Travel refers to the control over the user's viewpoint in three-dimensional space, while wayfinding refers to the cognitive process of determining a path based on knowledge of the environment, visual cues, and aids like maps or compasses [5]. During navigation, users often engage in additional tasks that require attention. In driving research, these tasks are commonly called secondary tasks or distractions [9, 40], and include any activity that requires or triggers attentional shifts away from the task of driving [26, 58]. Common examples of such tasks performed during driving include adjusting the sound system's volume, listening to a podcast, and conversing over the phone [74]. Despite their irrelevance to the task of navigation, secondary tasks influence the cognitive demand experienced in active exploration experiences because they impose their own attentional demands on the driver (user). With research increasingly showing the existence of a relationship between attentional demand and sickness [57, 68, 81], and the growing use of VR driving simulations for training, entertainment, and research [80], it bodes well for researchers to study how demands associated with secondary tasks performed during navigation affect sickness and discomfort.

Researchers have shown that increased workload experienced during virtual reality experiences tends to exacerbate perceived levels of sickness [68, 81]. It has been suggested that tasks that impose high mental demand render users with less cognitive resources to devote towards handling sickness symptoms, leading to an increase in the affliction's perceived severity [21]. If the maintenance of health is a task that requires cognitive resources in and of itself, then resource allocation to secondary tasks can increase sickness levels, as found in [94]. In contrast to these findings, however, researchers have also demonstrated favorable effects of secondary tasks as a means to distract users from perceiving the onset of sickness symptoms [3, 57, 84]. The exposition offered to explain such trends largely subscribes to the limited capacity model [30], positing that allocation of cognitive resources towards secondary tasks, limits the availability of resources required to cognitively process sickness, thereby leading to lower levels of its consciously perceived severity [84]. Collectively, the aforementioned findings exhibit a propositional disparity, suggesting that demand arising from secondary tasks can be favorable in some scenarios but unfavorable in others. Increased demand from secondary tasks may reduce sickness in highly sickening experiences by distracting users, but exacerbate perceived levels of the affliction in experiences that aren't sickening due to increased stress and workload. Consequently, the scientific community is still unclear about how secondary tasks and their demands affect sickness and

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Fig. 1: Virtual cityscape with one of its landmarks.

hence continues to investigate what appears to be an intricate relationship between these aspects. We attempt to contribute to this problem space, investigating how the demands of secondary tasks performed during active exploration affect cybersickness in IVEs. Apropos of this, we present the results of an empirical evaluation that appraises how cybersickness is affected by increased demand from secondary tasks encountered during navigation in differing sickness-inducing levels of an active exploration virtual experience.

2 Related Work

2.1 Cybersickness

Cybersickness commonly refers to the feeling of discomfort felt by users of VR, marked by motion sickness-like symptoms such as nausea, eye strain, sweating, dizziness, disorientation, etc. [41, 51, 60, 69]. Given its manifestation in IVEs that induce vection (perception of self-motion) primarily through visual stimulation (optic flow), this malady is commonly referred to as visually induced motion sickness (VIMS) [23, 34, 35, 47]. The 'sensory conflict theory' posits that sickness occurs when incoming sensory information is discrepant with expectations built through prior experience [59, 60, 71]. The 'postural instability theory' argues that the affliction arises due to an inability to maintain postural balance during motion [63]. The 'poison theory' claims that adverse stimulation causes the body to misread information, thinking that it has ingested toxins, leading to an emetic response [76]. While several such theories have sought to expound on the etiology of cybersickness [10], the 'sensory conflict' and 'postural instability' remain the most prominent in the research community [61]. Researchers commonly measure cybersickness using a combination of methods including questionnaires, verbal reports, and physiological markers [64]. While scales like the motion sickness assessment questionnaire (MSAQ) [19] and virtual environment performance assessment battery (VEPAB) [39] are sometimes used to measure sickness, the simulator sickness questionnaire (SSQ) [31] remains the de facto standard for self-reported measures of the affliction. The misery scale and fast motion sickness scale (FMS) involve periodic verbal reports on sickness levels, allowing for CS measurement during stimulus presentation [4, 32]. Variants of the FMS are also used [81, 82, 84], tailoring its periodicity and directional anchoring. We used the scale adopted in [15, 62, 91, 92], periodically measuring discomfort levels. Electrodermal activity (EDA) is an umbrella term used to define autonomic changes in the electrical properties of the skin. The EDA signal includes slowly changing background tonic (Skin Conductance Levels: SCL) and rapid phasic components (Skin Conductance Responses: SCR), arising from sympathetic neuronal activity [6]. The tonic SCL component of EDA is the absolute level of conductance in the absence of phasic responses [11], and involves changes in the skin's electrical conductance caused as a response to cybersickness amongst other factors [36]. Skin conductance levels have been shown to increase with motion sickness symptoms [27, 49], prompting its use as an operationalization of sickness in several studies [1, 82, 84]. Researchers generally encourage assessing self-reports and physiological measures of CS.

2.2 Secondary Tasks and Sickness

Secondary tasks are widely discussed in the context of driving research given their implication for road safety. Researchers interchangeably refer to them as distractions [2, 9, 40], defining them as any activity that draws a driver's attention away from the task of driving [26, 58]. In clinical research exploring the usage of distractions for pain relief, secondary tasks are considered processes that compete for attention against the salient sensations of pain [29]. Researchers studying the effects of secondary tasks on cybersickness generally subscribe to one of two major schools of thought. The first espouses the idea that engaging in a secondary task, by definition, requires additional attentional resources, thereby increasing the cognitive demand placed on a user. This resultant increase in attentional demand is expected to exacerbate sickness based on evidence showing that workload increases aggravate sickness symptoms [68, 81]. In contrast, the second school of thought champions the use of secondary tasks to distract users from the onset of sickness, making them less consciously aware, bothered, and disconcerted by its symptomatology [60, 84]. Investigations conducted in the past have shown evidence for both schools of thought, leaving the scientific community without a clear consensus on the topic. It is hence favorable to draw on literature, studying sickness and its connection to cognitive demand and secondary tasks.

Investigations favoring the exposition that increased task demands tend to exacerbate sickness symptoms suggest that high mental demand conditions render people with less cognitive resources to handle sickness symptoms [21, 81]. Recently conducted research showed evidence of the undesirable effects of increased task demands, demonstrating that cognitive demand increases applied by parametrically manipulating n in an n-back working memory task performed during travel increased perceived levels of sickness [68]. Work has also shown sickness-exacerbating effects of attentional demand increases in driving simulators [81]. The authors of this work call for researchers to decrease cognitive demand, citing increased sickness and reduced simulation-endurability from increased workload as inhibitors of VR technology adoption [81]. Similar deleterious effects of increased mental demand were also found by researchers using the cybersickness corn maze testbed [48]. A number of other efforts have documented similar findings [21, 56, 73], suggesting that engaging in secondary tasks - or multitasking can increase sickness [94]. The expositions used to support these findings largely consider the maintenance of health to be a task that requires attentional resources in and of itself, positing, per the information processing model [90], that engaging in additional tasks reduces the resources available for health-maintenance, consequently leading to greater sickness levels [68].

Research studies have also emerged showing merit for the use of secondary distractions as countermeasures against sickness. Auditory stimulation and music have been suggested as countermeasures against classical motion sickness [17, 67, 93]. The addition of a secondary mental distraction working memory task has even been found to reduce sickness induced by an off-vertical axis rotational chair [3]. In terms of VIMS, favorable sickness-reducing effects of distraction have been demonstrated on the application of pleasant music [33]. Users in this study watched a prerecorded video of a bicycle ride on a large screen in either the presence or absence of music which was further manipulated in terms of valence (relaxing, neutral, stressful). It was found that relaxing music significantly reduced perceived levels of VIMS. Similarly, pleasant odors have also been shown to help reduce VIMS [34]. In terms of fully immersive virtual environments achieved using tracked HMDs, an emerging trend of lower sickness levels was observed with the introduction of cognitive distractions [96]. Recent work on this front found that distraction in the form of a secondary rapid serial visual presentation (RSVP) task reduced sickness in a virtual rollercoaster ride [57]. More recently, research has demonstrated the efficacy of auditory, visual, and working memory secondary tasks as successful countermeasures against CS [84]. In this study, experimentally yoked triads of subjects were periodically exposed to distractors at discrete time points for short durations of time during an exploration experience. A control group that was not distracted reported significantly higher levels of sickness. The expositions generally offered to explain how such secondary distraction tasks reduce sickness are largely derived from the limited capacity model [30], explaining that a limited pool of information processing resources exists and that using capacity for one task limits the availability for another. Processing pain or sickness-related symptomatology is considered to require cognitive resources that are susceptible to interference from secondary tasks [46, 84]. This interference, per the multiple resource theory [88, 89], can prevent sickness from being cognitively processed, leading to a favorable reduction in perceived cybersickness levels through distraction.

Findings from these aforementioned studies indicate that increased secondary task demand may be favorable in highly sickening experiences by distracting users as shown in [3, 57, 84], but undesirable in experiences that are less sickening due to stress and workload as shown in [18, 68, 81]. Studying the effects of secondary task demand in differing levels of sickness-inducing simulations is hence pertinent, requiring the consideration of sickness-inducing triggers towards manipulating provocativeness. Chief among these triggers is rotational movement wherein users experience vection along the yaw, pitch, or roll axes [12, 28, 45]. There have been mixed findings on which of the three axes induces the most sickness with studies finding rotations along each to be nauseogenically provocative [45]. Inducing sickness through rotations along the yaw axis is favorable because it is more common, allowing for continuous exploration as called for in [84].

2.3 Contributions

While previous works have separately investigated how secondary tasks and task demands, in general, affect cybersickness, we are yet to see investigations that jointly and specifically study how the demands of secondary tasks performed during active exploration affect sickness. Our work seeks to contribute towards this end, further attempting to address an area of research called for by the authors of [84] towards determining whether increased demands from secondary tasks become overwhelming and stress-inducing rather than favorably more distracting from sickness depending on the provocativeness of the experience. Apropos of this, we discuss the results of an empirical evaluation, investigating how secondary task demand (STD) affects cybersickness in different sickness-inducing levels (SILs) of an active exploration experience, manipulations of the latter of which are realized by inducing movements along the yaw rotational axis during active exploration.

3 System Description

3.1 Apparatus

The IVE used for this study was built using the Unity 2021.2.2f1 game engine software and was rendered on an HTC Vive Pro Eye HMD using a computer equipped with an Intel i7-8700 processor, 32 GB of RAM, and an NVIDIA RTX 2080 graphics card. This HMD has a field of view of 110° with a frame refresh rate of 90 Hz. The HTC Vive Pro handheld controllers were used to facilitate virtual navigation through the virtual environment. Virtual navigation, as realized in [84], featured a smooth steering-based travel metaphor wherein the controller's touchpad supported translational movement, and the user's head orientation (virtual facing/heading direction) corresponded to the forward direction. This virtual travel technique is easy and intuitive to learn [77, 84], further confirmed by pilot studies. The maximum speed afforded was 22.3 miles per hour. This movement speed is faster than natural walking speeds and was adopted to increase the potential occurrence of cybersickness [37, 66], thus allowing us to study the affliction. Furthermore, contemporary VR games tend to involve movement speeds that are much higher than natural walking speeds, making the chosen speed ecologically valid. Users were seated atop a full-swivel chair that was stationary, allowing for only rotational movement for making turns in the exploration, identical to the setup used in [84]. This setup was used because it facilitates better exploration and spatial awareness, and is associated with more comfort than restrictive chairs [25]. Moreover, sitting mitigated fatigue and risks of falls that could have resulted from standing for the study's entirety. During pilot testing, we ensured a stable simulation framerate above the device's maximum refresh rate and calculated HMD latency using Niehorster et al.'s method [53], yielding an average latency of 13.67 milliseconds (SD=2.49) from ten samples. To avoid any entanglement of the HMD cable, the KIWI pulley system was used to suspend the cable from the ceiling.

3.2 Virtual Environment

We designed an expansive 120-block city with realistically scaled skyscrapers, apartment complexes, restaurants, etc. These buildings were laid out in a concentric pattern, alternating between tall and short buildings, enabling smooth and consistent optic flow [80, 81, 84]. The outskirts featured a mountainous landscape with vegetation cover. We modeled salient landmarks, evenly distributing them throughout the city. These landmarks included distinguishable structures like Ferris wheels, monuments, statues, etc., standing out prominently amidst the cityscape. City blocks with landmarks had large animated flags and museum exhibit-like signage boards containing the landmarks' names (Figure 1). The city also contained trees, road signs, and miscellaneous objects to enhance its realism.

3.3 Working Memory Task Stimuli

During exploration, users periodically engaged in a secondary task (see section 4.2.2). Each instance of this task featured an n-back working memory task that manifested aurally as employed in [3, 52, 84]. Each instance lasted for a randomly selected duration ranging from 26 to 34 seconds. Based on the selected duration, a series of random numbers between one and nine was generated and played back to the user with an inter-stimulus interval of 1.8 seconds. Every instance of the working-memory task was further programmed to occur once every two minutes such that the last generated number stimulus of the sequence occurred exactly 25 seconds before the following two-minute discomfort-sampling mark (Figure 2). This 25-second interval between the completion of the working memory task instance and the two-minute mark was chosen based on the average duration between stimuli completion and comfort scores sampled in [84]. As employed in [84], users' responses in the working memory task were recorded by the experimenter, and the numeric stimuli were fed to participants through the HMD's built-in headphones.

4 Experiment

4.1 Study Design

To empirically evaluate how the cognitive demands of secondary tasks affect cybersickness in different sickness-inducing levels of active exploration experiences, we employed a 2 (secondary task demand [STD]) X 2 (sickness-inducing level [SIL]) multifactorial design manipulating both independent variables as between-subjects factors. This meant that each user performed one of two mentally demanding secondary tasks (1-back or 2-back working memory task) under one of two sickness-inducing levels (low or high) of an active exploration task. Sections 4.2.1 and 4.2.2 detail these manipulations.

4.2 Tasks

Identical to the methodology adopted in [84], participants were tasked with performing two tasks while immersed in the IVE: an active exploration task (virtual travel) and a secondary working memory task. Participants were asked to weigh these tasks equally, performing both tasks to the best of their abilities. Participants in all cell block conditions were instructed to avoid stopping during the experience, continuing to virtually travel throughout the course of their session, as in [84]. The tasks are described in this section.

4.2.1 Active Exploration Task

This task involved participants navigating through a virtual city, and encountering landmarks along their way. The exploration route taken by participants involved virtual travel through the city along a predefined designated path. The exploration continued for the entirety of the study which lasted at most 40 minutes. Participants were told to pay attention to the landmarks and that they would be questioned about their locations at the end of the experience. The city consisted of a total of ten landmarks. To make participants familiar with the task, the first landmark was within viewing distance of the start point of the simulation. This task was designed to keep participants engaged and attentive to the environment, keeping them occupied with the active exploration of the city while experiencing high levels of optic flow, as employed in [81, 82, 84].

To ensure that all participants traveled through the same route through the city, a way-point ring collection scheme was implemented to guide participants' exploration, similar to methods employed in [84]. The way-points were collectible hollow green rings that sequentially appeared one after another upon collection, shepherding participants along a predefined exploration route. These hollow rings were used instead of solid objects to prevent participants from fixating on the way-points in trying to cope with sickness symptomatology. To collect a ring, participants had to simply pass through the ring, allowing for continuous virtual travel without halts to optic flow. Upon collection of a ring, it immediately disappeared and haptic feedback was provided to the users via a pulse generated on the handheld controller. The next ring would then appear at a predefined nearby location that was easily discoverable to the participant. The rings were laid out such that every successive ring did not require participants to stop and search but rather allowed for collection without breaks in virtual motion. A total of 446 way-point rings were sequentially spawned, one after another, at predefined locations to facilitate continuous and active exploration of the city, also mitigating extraneous influences of the exploration route.

Sickness-inducing Levels of Active Exploration Task (SILs)
To manipulate the SILs of the exploration task, we varied how frequently users experienced a simulated yaw-rotational reorientation effect during the exploration. Each reorientation would non-instantaneously adjust the yaw rotation of the user's viewpoint in the scene during exploration, requiring compensatory rotation (more optic flow) to correctly stay on the course of the exploration trail. The simulation was programmed to recurrently inject each reorientation randomly (clockwise or counter-clockwise) on either side of the user's forward-facing direction based on the heading vector sampled at that instant. The duration between successive reorientations was not regular but rather varied randomly within level-specific time ranges chosen for each SIL, dictating the frequency of their occurrence. The range chosen for the low SIL of the active exploration task featured this yaw-rotational effect re-occurring after a random duration selected between 12 and 14 seconds. The high SIL's range featured the effect re-occurring after a random duration selected between 6.5 and 8.5 seconds. These durational ranges for the two SILs were determined based on pilots taking into consideration the objectives of ensuring equivalent ranges, maximizing power, and ensuring that the simulation was sickness-inducing but not too provocative that it caused early termination. The magnitude of each reorientation was randomized across both SILs of the exploration task, ranging between 30° and 60°. This range was chosen because it features reorientation occurring within the user's field of view in the mid-peripheral region of vision, thereby allowing for continuous travel without the need to stop virtual motion, as called for in [84]. This was confirmed by 13 pilot subjects, suggesting that yaw rotations occurring within this range allowed users to continue performing the exploration without any cessation of virtual motion required to correctly stay on the exploration trail. The rate of every yaw rotation applied, regardless of angular magnitude, was kept fixed at a rotational speed of 30°/s in both SILs. The randomization of durations between successive yaw-rotations occurring within the level-specific ranges, and randomization of the angular magnitude of rotations applied within the 30° and 60° range was carried out to prevent users from calibrating and adopting strategies to compensate for the sickness-inducing effect, and working out when to expect its next occurrence. The yaw-rotational effects applied in both SILs of the exploration task was programmed to start after one minute (Figure 2), allowing users to perform a minute of yaw-rotation-free exploration, thereby enabling better acclimation to the travel metaphor. While methods like varying the speed of motion and frame rates were also considered, this manipulation method was chosen to keep the translational optic flow consistent between the SILs.

4.2.2 Secondary Working Memory Task

While navigating through the city, participants had to recurrently engage in an n-back working memory task. N-back tasks are commonly used in cognitive psychological research [50, 55, 85]. The task used

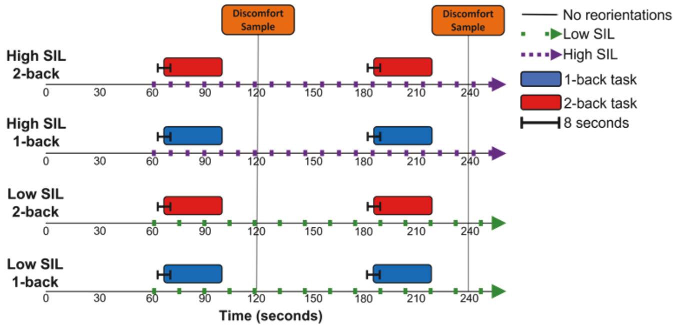

Fig. 2: Schematic representation of the experimental conditions in the experiment. The horizontal axis represents the time elapsed. Secondary task instances are represented by colored boxes. The different SILs of the exploration task are represented by color-coded dashed arrows. The dashing frequency of the colored arrows, on average, represents how frequently yaw-rotational reorientations ocurred in each SIL of the exploration task. The start point of these arrows corresponds to the time at which the reorientation effects were programmed to start ocurring.

in our study was adopted from [84], similarly manifesting aurally over discrete instances rather than requiring persistent attunement. For each instance of the task, participants heard a continuous series of random digits from one to nine. They would have to listen to the first n digits without responding and then for each following number heard, they would have to verbally respond with the digit they heard n digits ago. The inter-stimulus interval (time between 2 consecutive digits) was programmed to be 1.8 seconds. Each task instance lasted anywhere between 26 and 34 seconds. Participants were trained (in the real world) to perform the working memory task prior to starting their exploration in VR. This training phase continued until users could perform 10 consecutive trials of the task correctly.

Levels of Secondary Task Demand (STDs)
The secondary task's demand was manipulated by parametrically varying the number of digits required to be remembered in the working memory task. Accordingly, we utilized a 1-back and a 2-back working memory task. A 2-back task naturally requires more working memory resources than a 1-back task because more digits have to be continuously committed and released from users' working memory [55]. This parametric manipulation of n in the n-back task allowed us to realize the two levels of the secondary task's demand. While a 3-back task was considered in attempts to maximize power, it was not adopted because findings from pilot studies indicated that participants could not perform such a demanding task while also having to virtually navigate.

4.3 Measures

Cybersickness - We operationalized CS using a combination of self-reports and physiological measures. The first measure involved computed differences between the post and pre-instances of the SSQ questionnaire described in [31]. Our second measure involved periodic verbal reports of discomfort levels on a 0 to 10 scale, sampled every two minutes from the start of the exploration. This method of measurement has been employed in [15, 62]. Our third measure was based on the tonic component of the electrodermal activity (EDA) signal through skin conductance levels (SCL) which is often used as a temporal physiological measure of cybersickness [1, 81, 84].
Spatial Memory - After the simulation, users were provided with images of all landmarks and a top-down view of the city on which they indicated where each landmark was. The Euclidean distances between the indicated and actual locations of each landmark were computed. The angles between the vectors formed from the start position to the indicated and actual locations of each landmark were also computed. These Euclidean distances and angular differences were aggregated and averaged for all landmarks forming two dependent variables indicative of the spatial distance error and spatial orientation error respectively.
Navigational Performance - For each user, the number of way-points/rings collected per minute was used as an operational measure

of navigational performance, as in [84]. This measure indicates how well users could navigate in the virtual environment, correctly staying on the course of the designated exploration trail.

4.4 Research Questions and Hypotheses

We specifically aimed to answer the following research question: "How do the attentional demands associated with secondary tasks affect cybersickness in different levels of sickness-inducing active exploration experiences?" Downstream of this, we were also interested in ascertaining if the manipulations affected other aspects of the VR experience like spatial memory, navigational performance, etc. We operationalized cybersickness, spatial memory, and navigational performance using measures described in section 4.3. Based on this research question, we developed the following hypotheses that reflect the work discussed in section 2 and subsequent portions of this section:

H1: The exploration task's high SIL will result in higher levels of sickness than the low SIL of this task, indicating successful manipulation.

H2: The effect of STD on cybersickness will be moderated by the SIL of the exploration task. Increased demand from the 2-back will increase sickness levels in the exploration task's low SIL but reduce sickness levels in the exploration task's high SIL.

H3: Compared to the low SIL, users experiencing the high SIL of the exploration task will terminate their simulations sooner.

H4: Compared to the 1-back, performing the 2-back secondary task during exploration will result in lower spatial memory scores.

H5: Compared to the 1-back, performing the 2-back secondary task during exploration will result in inferior navigational performance.

Increasing the frequency of the simulated yaw-rotational effect entails a larger number of reorientations occurring during exploration. This should result in users having to make a larger number of compensatory actions to correctly stay on the course of the exploration trail, thereby exposing them to more optic flow. Given this increased optic flow and the proclivity for scene rotational movements to increase sickness [45], it is expected that the high SIL of the exploration task will work as intended and produce higher levels of sickness than the low SIL of this task, also reducing how endurable the simulation is. Attending to a secondary task consumes attentional resources, which are finite [30], leaving less cognitive capacity available for processing pain, discomfort, and the conscious perceptions of symptomatological effects of cybersickness [42, 46, 84]. Researchers are increasingly showing evidence that supports this exposition, demonstrating the efficacy of distractions as a countermeasure against sickness [3, 57, 84, 96]. If this is indeed the case, a more demanding secondary task should result in lower levels of sickness when a simulation is highly sickening. In less sickening experiences, however, increased demand from a secondary task may increase sickness because of increased workload, cognitive fatigue, and stress [18, 38, 68, 81]. It is hence expected that the STD moderate the effects of the exploration task's SIL. Driving research shows that secondary distraction tasks compromise driving performance and road safety [95], making increases in their demand likely to worsen spatial memory and navigational performance.

4.5 Participants

An apriori power analysis using G*Power revealed that for a study of four groups, at least ten samples of temporal sickness measures per participant, $\alpha = 0.05$, power (1-β) = 0.95, correlation among repeated measures of 0.5, the estimated sample size was 32. Thus, a total of 44 participants were recruited for this Institutional Review Board (IRB) approved study at Clemson University, with 11 allotted per condition. Participants were recruited using flyers posted around campus. Their ages ranged from 18 to 35 years (M=24.14, SD=3.86), 17 of whom were females and the rest male. All participants had normal or corrected-to-normal (20/20) vision. Given the simulation's tendency to induce sickness, individuals with any history of epilepsy or vertigo were excluded from participating in the study. Users who indicated having feelings of fatigue, discomfort, and body pain were also excluded from participation. Identical to [84], individual differences in sickness-susceptibilities were accounted for in the analyses by controlling, as a covariate, the motion sickness susceptibility scores obtained from administering the MSSQ [20]. In terms of VR experience, a total of 17 participants reported having less than one hour, 16 reported having 2-5 hours, six reported having 6-9 hours, and five reported having over 10 hours. In terms of video game experience obtained on a 7-point Likert scale, five users reported a score of 7, nine users reported a score of 1, and all other users reported scores ranging between 2-5. Overall, VR and game experience did not significantly differ across conditions.

4.6 Procedure

Upon arriving at the laboratory, participants were greeted and asked to read and sign a consent form (informed consent). After consenting to participate in the study, participants filled out a demographics questionnaire that included questions about their backgrounds, experience with VR and video games, tolerances to physiological discomforts, working memory abilities [78], and distraction susceptibility (SDDQ) [13]. This was followed by the SSQ [31]. After completing the pre-experiment questionnaires, participants were randomly assigned to one of the four experimental cell block conditions. The following describes the procedural sequence that all users participating in the study went through:

1. Upon survey completion, participants were seated on a full-swivel chair and instructed about the tasks. The instructions did not mention anything about the simulation making them sick because we did not want to prime them. However, users were told that they could request termination at any time.
2. The experimenter then explained how to use the VIVE controllers, thoroughly training the participants on the navigation metaphor. It was ensured that this training took place in the real world (not in VR) to avoid any carryover effects of cybersickness that could have ensued from a VR training phase.
3. Participants were then instructed to verbally report their levels of discomfort on the 0 to 10-point scale whenever they heard an audio clip question that was played by the simulation (every two minutes), as employed in [81, 82, 84].
4. The Empatica Embrace Plus was then strapped to the participants' wrists. This device sampled users' skin conductance levels four times every second (sampling frequency of 4 Hz). The HMD (adjusted IPD) was then calibrated to track users' eye movements.
5. Participants then wore the HMD and began the exploration, performing the tasks. The experience ended either when participants requested termination, or when 40 minutes elapsed.
6. After the simulation, participants filled out the SSQ again [31], a questionnaire on spatial memory (see section 4.3), and the MSSQ [20]. Participants were given refreshments and were allowed to take breaks during the post-surveys but it was ensured that the SSQ and spatial memory questionnaires were completed immediately after the simulation ended.
7. A semi-structured debriefing interview was then conducted. Upon conclusion, it was ensured that users reported being free of sickness symptoms before they could depart, failing which they were ushered to the health center across the building. Three users were directed to the health center due to such discomfort.

5 Results

Parametric analyses were conducted on the measures obtained from the SSQ questionnaire, discomfort levels, EDA-SCL, spatial memory scores, and navigational performance scores after ensuring that the assumptions of each test used were met. This included ensuring normal distribution of the data across the levels of the categorical predictors, homogeneity of variance using Levene's tests, linear relationships between covariates and the dependent variable, homogeneity of the covariate's regression slopes across conditions, Box's test of equality of the covariance matrix was not violated, error variance in groups of samples were equivalent using Mauchly's test of sphericity. Post-hoc pairwise comparisons between levels of the between-subjects variables were conducted using Tukey's HSD test and between levels of within-subjects variables were conducted using the Bonferroni corrected alpha method. Two users exhibited intense emetic responses and one other became severely unsettled early into the simulation. Data from these three participants were excluded from the analyses and those from all other users were included in the analyses given that they spent a

	Sickness Inducing Level (SIL)		**Secondary Task Demand (STD)**	
	Low	**High**	**1-back**	**2-back**
TS	SIL: F(1,34) = 21.56, $p < .001$, $\eta_p{}^2$=.388 STD: F(1,34) = 7.79, $p < .01$, $\eta_p{}^2$=.186 MSSQ: F(1,34) = 7.24, $p = .011$, $\eta_p{}^2$=.186			
	58.22 ±8.25	111.85 ±8.07∗	67.52 ±8.44	102.56 ±8.61∗
N	SIL: F(1, 34) = 32.30, $p < .001$, $\eta_p{}^2$=.49 STD: F(1,34) = 19.60, $p < .001$, $\eta_p{}^2$=.37 MSSQ: F(1,34) = 14.11, $p < .001$, $\eta_p{}^2$=.293			
	53.10 ±7.29	112.88 ±7.58∗	57.49 ±7.46	108.49 ±8.13∗
O	SIL: F(1,35) = 8.36, $p < .01$, $\eta_p{}^2$=.351 STD: F(1,35) = 3.17, $p = .08$, $\eta_p{}^2$=.083 MSSQ: F(1,35) = 4.36, $p = .044$, $\eta_p{}^2$=.11			
	42.79 ±6.44	68.49 ±6.12∗	47.00 ±6.59	64.28 ±6.56
D	SIL: F(1,33) = 17.88, $p < .001$, $\eta_p{}^2$=.351 STD: F(1,33) = 5.98, $p = .02$, $\eta_p{}^2$=.153 MSSQ: F(1,33) = 7.14, $p = .03$, $\eta_p{}^2$=.135			
	63.34 ±10.61	126.86 ±10.62∗	75.14 ±11.10	115.06 ±11.08∗

Table 1: Results of Two-way ANCOVA analyses on the SSQ dimensions of total sickness (TS), nausea (N), oculomotor (O), and disorientation (D) for each of the two levels of the manipulated factors. Interaction effects between the two factors (not listed) were not significant on any of the dimensions. Motion sickness susceptibility (MSSQ) was controlled as a covariate. Values significantly different from baseline levels of each manipulated factor are denoted by *.

minimum of eight minutes in the simulation. On average, users endured the simulation for 23 minutes. Prior to running all analyses, outliers were removed by deleting standardized residuals greater than 2. In each analysis, significant effects are presented with measures of effect size. The $\eta_p{}^2$ represents the proportion of variance explained by a given variable of the total variance remaining after accounting for the variance explained by other variables in the model.

5.1 SSQ

The SSQ difference scores (nausea (N), oculomotor (O), disorientation (D), and total score (TS)) between the pre and post-tests were submitted to a general linear model Two-way ANCOVA using SIL and STD as fixed independent factors while controlling for motion sickness susceptibility (MSSQ scores) as a covariate to account for individual differences. Table 1 depicts the results of these analyses.

After controlling for motion sickness susceptibility, we found main effects of the SIL factor on total sickness ($p < .001$), disorientation ($p < .001$), oculomotor discomfort ($p < .01$), and nausea ($p < .001$). We also found main effects of the STD factor on total sickness ($p < .001$), disorientation ($p < .001$), and nausea ($p < .001$) after controlling for the covariate. There were no significant interaction effects between the SIL and STD factors found on any of the four dimensions produced by the SSQ questionnaire ($p > .05$). The covariate, motion sickness susceptibility, was found to significantly predict total sickness ($p = .011$), disorientation ($p = .03$), oculomotor discomfort ($p = .044$), and nausea ($p < .001$), indicating that those more susceptible to motion sickness reported higher levels of sickness on all these dimensions.

Post-hoc tests revealed that the covariate-adjusted mean of total sickness in the high SIL of the exploration task was significantly higher than the low SIL of this task ($p < .001$). Post-hoc tests revealed that the covariate-adjusted mean of total sickness in the 2-back level of the STD was significantly higher than the 1-back level of the STD ($p < .01$).

Post-hoc tests revealed that the covariate-adjusted mean of nausea levels in the high SIL of the exploration task was significantly higher than the low SIL of this task ($p < .001$). Post-hoc tests revealed that the covariate-adjusted mean of nausea levels in the 2-back level was significantly higher than the 1-back level of the STD ($p < .001$).

Post-hoc tests revealed that the covariate-adjusted mean of oculomotor discomfort levels in the high SIL of the exploration task was significantly higher than the low SIL of this task ($p < .01$). Post-hoc tests revealed that the covariate-adjusted mean of oculomotor discomfort levels in the 2-back level of the STD was marginally higher than the 1-back level of the STD ($p = .08$).

Post-hoc tests revealed that the covariate-adjusted mean of disorientation in the high SIL of the exploration task was significantly higher than this task's low SIL ($p < .001$). Post-hoc tests revealed that the covariate-adjusted mean of disorientation in the 2-back level was significantly higher than the 1-back level of STD ($p = .02$).

5.2 Temporal Measures (Discomfort Levels & EDA-SCL)

The temporal aspects of the affliction were studied based on the periodically sampled discomfort levels and the EDA-SCL levels gathered from the Empatica Embrace-Plus sensor. To account for individual differences between participants in the physiological markers of EDA-SCL, the data obtained from each user was normalized using a min-max normalization, producing scores ranging between 0 and 1. The normalized EDA data was then averaged across one-minute intervals to assess the overall EDA at each minute, similar to methods employed in [82, 84]. Since repeated measures of discomfort levels and EDA-SCL were obtained for each participant, the variables had considerable nesting. Given that participants were free to terminate sessions whenever they felt disconcerted, each user had a different number of samples on each of these dependent measures. Additionally, the introduction of a repeated measures variable produced multiple levels of variance in the data: variance occurring within participants and variance occurring between participants. As these dependent measures were measured over multiple time steps for each participant, a portion of their variances can be attributed to a common source – the participants themselves. Level 1 (within-participant) variables represent those that change between time steps (the time step number itself). Level 2 (between-participant) variables represent those that change from participant to participant (the condition). To properly account for variance both between and within subjects, Hierarchical Linear Modeling was used, identical to [84]. Instead of using a single regression equation to represent the entire dataset, HLM produces a model in which the within-participant variables predict the dependent variable, followed by a model in which between-participant variables predict the slope and intercept of the first model [24]. In other words, HLM allows researchers to model how the effects of within-participant variables are affected by between-participant variables. Furthermore, HLM is robust enough to account for different numbers of measurement occasions across participants [54]. The Intra-Class Coefficient (ICC) indexes the percentage of total variance found at the between-subjects level.

Prior to conducting the analyses, the extent of nesting in the data was assessed by computing the ICC from the null model for the discomfort levels and EDA separately. The ICC for the discomfort levels was calculated to be 0.25, indicating that approximately 25% of the variance in discomfort was associated with the participant and that the assumption of independence was violated. Similarly, the ICC was calculated to be 0.18 for the EDA levels. Following a multilevel modeling technique is deemed ideal in this case. For the analysis of each of these dependent variables, an initial main effects model was run, such that all main effects (Level 1 and Level 2) were included in the analysis at once. Results for each of these main effects are reported from the initial main effects model. To analyze the interaction, the interaction term was added to the main effects model. Effect sizes for each fixed effect are presented as the change in R^2 (proportion of variance explained) comparing the model that includes the effect and the same model with the effect removed. The resulting sr^2 (semi-partial R^2) is the percentage of variance uniquely accounted for by the fixed effect [70]. For all the following models in the analyses, the only random effect computed was the intercept based on the Participant ID.

5.2.1 Discomfort Levels

A linear mixed effects model was run to assess the effects of SIL, STD, and time step on the periodically sampled discomfort levels. This model with only the main effects (AIC = 2073.17, df = 6) offered a significantly better fit to the data than did the null model (AIC = 2309.71, df = 3), $\Delta\chi^2(3) = 242.54$, $p < .001$. The model explained

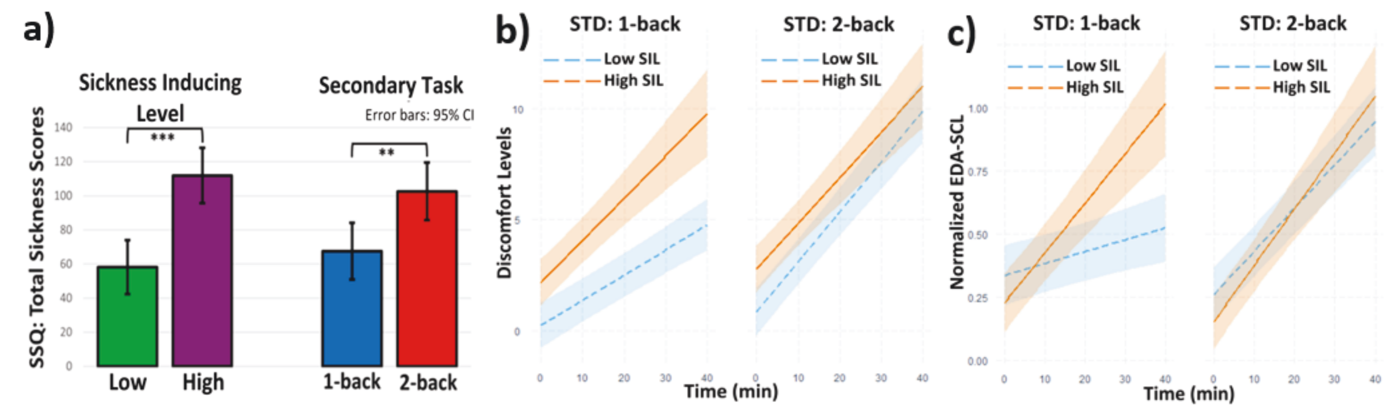

Fig. 3: (a) Covariate adjusted main effects of exploration task's SIL and STD on SSQ Total Scores (b) Change in discomfort over time in the 2 levels of STD moderated by the effects of the exploration task's SIL; (c) Change in normalized EDA-SCL over time in the 2 levels of STD moderated by the effects of the exploration task's SIL. Error bars and shading around each line indicate 95% confidence intervals.

63% of the variance in the discomfort levels (conditional $R^2 = 0.63$, marginal $R^2 = 0.38$). The results suggest a significant effect of time step on discomfort levels, F(1, 436) = 313.23, $p < .001$, $sr^2 = 0.30$. As the time step increased by 1 standard deviation (SD) units, the discomfort levels increased by 0.16 SD units. There was also a significant effect of the SIL of the exploration task on the discomfort scores, F(1, 36) = 4.70, $p = 0.04$, $sr^2 = 0.06$. Participants had a higher discomfort score in the high SIL of the exploration task (M=5.12, SE=0.40) as compared to the low SIL (M=2.87, SE=0.38). There was also a significant effect of the STD on discomfort, F(1, 36) = 4.71, $p = 0.04$, $sr^2 = 0.04$. Participants had higher discomfort levels when performing the 2-back task (M=4.75, SE=0.40) as compared to the 1-back task (M=3.24, SE=0.38).

The exploration task's SIL was a significant moderator of the effect of time on discomfort, F(1, 435) = 4.96, $p = .03$, $sr^2 = 0.01$. That is, the SIL altered the slope (or rate of change) of the relationship between time step and discomfort. A test of simple slopes revealed that for each SIL of the exploration task, the simple slope for time step was positive and significantly different from zero. The exploration task's high SIL ($B = 0.198$, $SE = 0.019$, $t = 10.70$, $p < .001$) had a steeper positive slope than the low SIL ($B = 0.150$, $SE = 0.010$, $t = 14.54$, $p < .001$).

The STD also significant moderated the effect of time step on discomfort, F(1, 435) = 26.52, $p < .001$, $sr^2 = 0.04$. A test of simple slopes revealed that for each level of the STD, the simple slope for time step was positive and significantly different from zero. The 2-back task ($B = 0.22$, $SE = 0.01$, $t = 15.27$, $p < .001$) had a steeper positive slope than the 1-back task ($B = 0.13$, $SE = 0.01$, $t = 11.43$, $p < .001$).

The three-way interaction between the exploration task's SIL, STD, and time step was also significant, F(1, 433) = 4.56, $p = .03$, $sr^2 = 0.05$. As seen in Figure 3, a test of simple slopes for time step revealed that, when users performed a 1-back secondary task, the low SIL ($B = 0.115$, $SE = 0.012$, $t = 9.37$, $p < .001$) and high SIL ($B = 0.189$, $SE = 0.026$, $t = 7.35$, $p < .001$) of the exploration task had positive slopes significantly different from zero. Similarly, when performing a 2-back secondary task, the low SIL ($B = 0.226$, $SE = 0.018$, $t = 12.90$, $p < .001$) and high SIL of the exploration task ($B = 0.209$, $SE = 0.025$, $t = 8.31$, $p < .001$) had steeper positive slopes significantly different from zero.

5.2.2 EDA-SCL

A linear mixed effects model was run to assess the effects of SIL, STD, and time step on the normalized EDA-SCL levels. This model with only the main effects (AIC = 293.88, df = 6) offered a significantly better fit to the data than did the null model (AIC = 445.49, df = 3), $\Delta\chi^2(3) = 157.61$, $p < .001$. The model explained 36% of the variance in the normalized EDA (conditional $R^2 = 0.36$, marginal $R^2 = 0.17$). The results suggest a significant effect of time step on the normalized EDA-SCL levels, F (1, 802) = 170.72, $p < .001$, $sr^2 = 0.16$. As the time step increased by 1 standard deviation (SD) units, the normalized EDA-SCL levels increased by 0.01 SD units. There were no significant main effects of SIL or STD on the EDA-SCL.

The SIL of the exploration task was a significant moderator for the effect of time step on normalized EDA levels, F(1, 801) = 23.89, $p < .001$, $sr^2 = 0.02$. That is, this task's SIL altered the slope (or rate of change) of the relationship between time step and normalized EDA levels. A test of simple slopes revealed that for each SIL level of this task, the simple slope for time step was positive and significantly different from zero. The high SIL of this task ($B = 0.021$, $SE = 0.002$, $t = 10.85$, $p < .001$) had a steeper positive slope as compared to the low SIL of this task ($B = 0.010$, $SE = 0.001$, $t = 9.21$, $p < .001$). The STD was also a significant moderator of the effect of time step on normalized EDA levels, F(1, 801) = 32.42, $p < .001$, $sr^2 = 0.04$. A test of simple slopes revealed that for each level of the STD, the simple slope for time step was positive and significantly different from zero. The 2-back task ($B = 0.018$, $SE = 0.001$, $t = 13.23$, $p < .001$) had a steeper positive slope than the 1-back task ($B = 0.008$, $SE = 0.001$, $t = 6.06$, $p < .001$).

The three-way interaction between SIL, STD, and time was also significant, F(1, 799) = 5.89, $p = .02$, $sr^2 = 0.07$. A test of simple slopes for time step revealed that, when users performed a 1-back secondary task, the low SIL ($B = 0.005$, $SE = 0.001$, $t = 3.18$, $p = .002$) and high SIL ($B = 0.020$, $SE = 0.003$, $t = 7.32$, $p < .001$) had positive slopes significantly different from zero. Similarly, when performing a 2-back secondary task, the low SIL ($B = 0.017$, $SE = 0.002$, $t = 10.65$, $p < .001$) and high SIL ($B = 0.022$, $SE = 0.003$, $t = 8.36$, $p < .001$) had steeper positive slopes significantly different from zero. (Figure 3c)

5.3 Duration

A Two-way ANOVA was conducted to determine the effects of SIL and STD on the duration after which users terminated their simulations. We found a significant interaction effect between these factors, F(1, 34) = 4.77, $p = .036$, $\eta_p{}^2 = 0.123$; a significant main effect of the exploration task's SIL, F(1, 34) = 49.354, $p < .001$, $\eta_p{}^2 = .592$; and no significant main effect of STD ($p = .104$). The duration after which participants terminated the session was significantly lower ($p = .036$) in the 2-back level of the STD (M = 26.738, SE = 2.582) than in the 1-back level of the STD (M = 36.965, SE = 2.722) when the exploration task's SIL was low but not when the exploration task's SIL was high.

5.4 Spatial Memory

A Two-way ANOVA was used to determine the effects of the exploration task's SIL and the STD on the averaged spatial distance errors. We found a significant main effect of STD, F(1, 37) = 4.573, $p = .039$, $\eta_p{}^2 = .11$; no significant main effect of the exploration task's SIL ($p = .67$); and no significant interaction effect ($p = .73$). The averaged error distances were significantly higher in the 2-back (M = 743.60, SE = 28.70) than in the 1-back level of STD (M = 657.78, SE = 28.04). In terms of spatial orientation errors, we found no significant main or interaction effects of SIL and STD ($p > .05$).

5.5 Navigational Performance

A Two-way ANOVA was conducted to determine the effects of the exploration task's SIL and the STD on the navigational performance (number of waypoint rings collected per minute). We found a significant main effect of the exploration task's SIL F(1, 35) = 12.332, $p < .01$, $\eta_p{}^2 = .261$; a significant main effect of the STD F(1, 35) = 13.401,

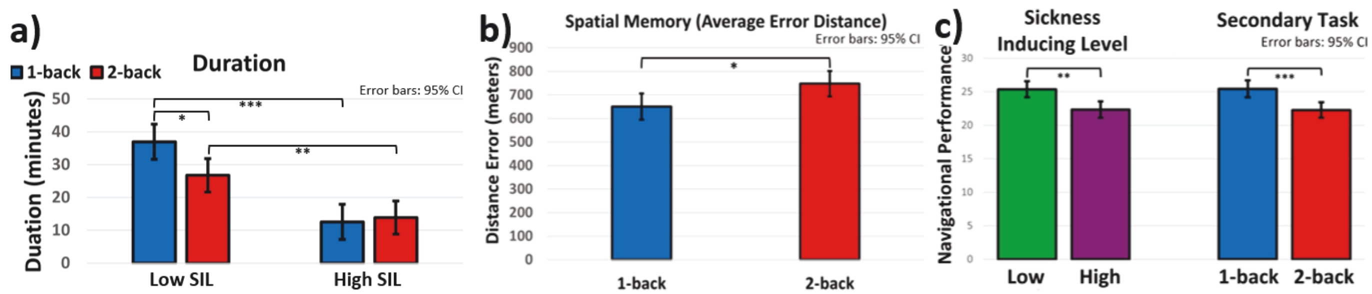

Fig. 4: (a) Effects of exploration task's SIL on simulation termination time moderated by STD; (b) Average Euclidean distance between the actual and indicated locations of a landmark for the two levels of the STD; and (c) Navigational Performance in the two SIL levels of the exploration task, and for the two levels of the STD. '*' denotes $p < 0.05$, '**' denotes $p < 0.01$, and '***' denotes $p < 0.001$.

$p < .001$, $\eta_p{}^2 = .277$; and no significant interaction effect between these factors ($p = .622$). As seen in Figure 4c, the performance was significantly worse in the exploration task's high SIL (M = 22.34, SE = 0.618) as compared to this task's low SIL (M = 25.36, SE = 0.604), and the navigational performance was significantly worse when the secondary task was a 2-back (M = 22.27, SE = 0.587) than when it was a 1-back (M = 25.43, SE = 0.634).

6 Discussion

6.1 Cybersickness

The statistical analyses of the SSQ scores revealed that after accounting for individual differences in motion sickness susceptibility, the exploration task's high SIL induced more sickness than the low SIL of this task. This increase in sickness caused by the increase in frequency of the applied yaw-rotational effect was also observed in the temporal measures of sickness (discomfort levels & EDA-SCL) wherein the high SIL was generally associated with a faster temporal onset of cybersickness than the low SIL (Figures 3b & 3c). These results offered support for hypothesis **H1**, indicating that increasing the frequency of the yaw-rotational effect worked as intended in inducing higher levels of sickness. Similar to results obtained by the authors of [28, 45], we found that increases in scene rotational movements increase the levels of cybersickness with increased optic flow.

Analyses carried out on the effects of the STD on cybersickness gave us some interesting insights. In the SSQ questionnaire, after accounting for individual differences in sickness susceptibilities, we found a main effect of STD, indicating that performing a 2-back secondary task resulted in higher sickness levels than performing a 1-back task (Figure 3a). Considering the effects of STD on the temporal measures of sickness (both verbally reported discomfort levels and physiologically measured EDA-SCL), we found 3-way interaction effects showing that the STD's effects on the rate of increase in sickness were moderated by the exploration task's SIL (Figures 3b & 3c). It can be seen that regardless of the STD levels (1-back vs 2-back), the high SIL of the exploration task led to the fastest increases in sickness levels. Interestingly, when performing a more attentionally demanding secondary task - in this case, a 2-back task - a clear and notable escalation in sickness was observed in the low SIL of the exploration task. As we hypothesized, more demanding secondary tasks seem to increase sickness in experiences that are less sickening because of increased workload, cognitive fatigue, and stress [18, 38, 68, 81]. Based on the limited capacity model [30], it was expected that increases in the attentional demands associated with the secondary task would limit the availability of resources available to process the manifestation of sickness symptomatology, thereby reducing its perceived severity in the exploration task's high SIL. Instead, we found that the exploration task's SIL, when high, produced a sort of ceiling effect that overshadowed the effects of the secondary task's attentional demand on cybersickness. The deleterious effects of increased STD were, as expected, only prominent in the low SIL of the exploration task but the expected favorable distractive effects of increased STD in the exploration task's high SIL were not observed. These results offered partial support for hypothesis **H2**, indicating that the effect of a secondary task's demand on sickness is moderated by how sickness-inducing an exploration is. We find that the increased attentional demands associated with secondary tasks performed during navigation can more quickly worsen how users feel, especially when the task of exploration is not already highly sickening to begin with.

Our results generally indicate that it is important to avoid increasing demands from secondary tasks performed during navigation as this can exacerbate sickness. This aligns with previous research showing that workload increases exacerbate sickness levels [68, 81], extending the same to scenarios involving increased demand from secondary tasks. In contrast to efforts demonstrating sickness-reducing effects from secondary distractions [3, 57, 84, 96], we did not obtain support for the exposition derived from the limited capacity model [30] adopted to explain such trends. Given the results of the aforementioned studies showing merit in the use of secondary tasks against sickness, our results suggest that the relationship between a secondary task's demand and cybersickness may be non-linear, as speculated in [68, 84]. Recent research exploring the relationship between pain and cognition has found something similar, in that cognitive distraction successfully reduced pain up until a certain point after which the relationship became reversed [43]. Similarly, secondary distraction tasks, if indeed useful, may potentially serve as a countermeasure against the affliction until a certain threshold beyond which increases in their attentional demands can exacerbate or have little influence on perceived levels of the affliction. The results obtained in the current study suggest that we may have crossed this threshold - if indeed, there exists one - in employing the 2-back task, leading to undesirable increases in sickness. Further research is required to study this intricate relationship between secondary task demand and sickness, allowing us to precisely determine where exactly this threshold lies.

6.2 Enduring VR simulations

Analyses conducted on the duration after which users requested termination due to sickness revealed a main effect of the exploration task's SIL wherein the high SIL level of this task led to faster termination of the session in comparison to the low SIL of this task. This result supports hypothesis **H3**, indicating that increased sickness levels can lead to a diminished ability to continue enduring a VR experience [81, 84]. Interestingly, a significant interaction effect was found between the exploration task's SIL and the STD. It was found that performing a 2-back task resulted in faster termination in the low SIL of the exploration task but not in the high SIL (Figure 4a). As can be seen, in the exploration task's high SIL, the attentional demand of the secondary task seems to have little influence on duration due to a potential overshadowing effect caused by the SIL of the exploration task. The negative influential effect of increased secondary task demand can be seen when the exploration is not already highly sickening to begin with. These results directly converge with our findings obtained in measures of sickness obtained from the periodically sampled discomfort levels and physiological markers of skin conductance, indicating that increases in a secondary task's demand can lead to a diminished ability of users to continue enduring VR exploration experiences, especially in those that are not already highly sickening to begin with.

6.3 Spatial Memory

The analyses conducted on the two measures of spatial memory provided some interesting insights. We found a main effect of the STD on users' average spatial distance errors. Performing a 2-back task resulted in users indicating the landmarks' positions further away than they actually were significantly more so than when performing a 1-back task (Figure 4b). Interestingly, we did not observe a similar detrimental effect of increased secondary task demand on the average spatial orientation errors, thereby offering partial support for hypothesis **H4**. Taking these results together, it appears that increases in the attentional demands of secondary tasks performed during exploration lead to more inaccurate estimates of where landmarks actually are located in terms of distance but not necessarily in terms of direction. Real-world research efforts have obtained similar findings, in that accuracies of spatial distance estimates do not correlate significantly with users' sense of direction [8]. This difference in sensitivity to spatial distance and directional judgments has also been observed in other real-world studies [7,75]. Our findings extend those aforementioned to VR contexts, showing that more demanding secondary tasks performed during exploration are likely to make one perceive landmarks to be farther away than they actually are without necessarily affecting their directional sense of where the landmarks are situated in immersive virtual space.

6.4 Navigational Performance

Regarding navigational performance, we found main effects of the exploration task's SIL as well as STD. In the exploration task's high SIL, the number of rings collected per minute was significantly lower than in this task's low SIL (Figure 4c). This is understandable because the increased frequency of reorientations likely made it more challenging for users to correctly steer themselves along the exploration trail, or also because increased sickness generally worsens task and navigational performance [36,65,72,87]. Given the nature of the manipulation performed to realize the two SILs in our study, our results on this front have to be interpreted, noting that it is not possible to isolate increased sickness as the causative factor that degraded navigational performance in the high SIL because the effects observed may have simply occurred as a consequence of the increased number of reorientations compromising effective navigation. In terms of STD, we found that when performing a 2-back, users were significantly worse at navigation than when performing a 1-back task (Figure 4c). This indicated that users' ability to successfully stay on the course of the exploration trail declined when performing a more attentionally demanding secondary task, thereby supporting hypothesis **H5**. This suggests that increases in attentional loads of secondary tasks performed during virtual navigation can lead to an undesirable degradation in how well users are able to navigate, aligning with real-world driving research showing the same [14,95].

6.5 Summary, Scope, and Limitations

This study provided us with some interesting insights into how secondary task demands affect important aspects associated with VR active exploration experiences. We learned that increased attentional loads from secondary tasks performed during navigation can exacerbate sickness levels. These deleterious effects seem especially prominent in experiences that are not already highly sickening to begin with. In situations where a simulation is already known to involve provocative motion, the harmful effects of increased demand from a secondary task seem to be overshadowed by how sickening the experience is. Increased secondary task demands also tend to reduce how long users can endure simulations that aren't already highly provocative. We also learned that more demanding secondary tasks reduce how well users can navigate as well as how accurately they remember distances to landmarks in virtual environments. It thus appears that increased demand from secondary tasks performed during navigation tends to generally produce undesirable effects on the VR experience. For these reasons, designers of VR applications featuring exploration must strive to reduce the demands of additional tasks performed during navigation towards holistically enhancing virtual experiences. Taking into consideration the favorable effects found by some researchers on using distractions against sickness, it appears as though there may be a non-linear relationship between a secondary task's demand and its effects on sickness. Apropos of this, there may be a threshold until which a distraction task can serve usefully in reducing sickness, crossing which can end up exacerbating or having little influence on perceived levels of the affliction.

In this study, participants were explicitly told to perform both the exploration and the n-back task. However, secondary tasks are often self-initiated or are under voluntary control like in multitasking or consciously thinking about something while navigating. We cannot be certain that demand arising from secondary tasks will generally produce the observed effects but can rather expect such effects to occur in situations where users are tasked with optimizing performance in both tasks. Our findings on the effects of the secondary task's demand must hence be carefully interpreted, considering the nature of the task and the grounds for its induction. Furthermore, the n-back task employed in this study, though not negatively valenced, differs from distractions commonly encountered during navigation and can be considered a stress-inducing task especially when performed for longer periods. This task was chosen because it affords researchers the ability to parametrically manipulate attentional load [55]. If the secondary task employed was positively valenced as in the case of pleasant music, it cannot be claimed that attentional demand increases - although it is unclear as to how this can be realized with music - will result in similar effects on cybersickness. It is hence appropriate to limit the scope of our findings to secondary tasks that are similar in nature and valence to those employed in this study. Notwithstanding experimental control over the exploration route taken by users in our study, affording motion control (active exploration) consequentially results in a loss of ability to precisely control visual motion stimuli across users. This inability of our experimental protocol to rigorously control visual motion stimuli that users received can be considered a limitation of this work. Despite this, we believe our findings are still valid because users traveled along the same route, continuously moving throughout the exploration, as in [84]. The device used to measure EDA, though relatively new, has come under scrutiny for limitations like its low sampling rate and inaccuracies when worn at the wrist. To address these limitations, we ensured that best practices were followed, consulting the manufacturer's technical team on how and where to secure the device on users' hands to enable seamless data collection.

7 Conclusion and Future Work

In this work, we investigated how demand from secondary tasks performed during active exploration affects cybersickness in IVEs. Using a multi-factorial study design we studied how two different demand levels of a secondary working memory n-back task (1-back and 2-back) affected sickness and other aspects associated with two different sickness-inducing levels of an active exploration virtual experience. The provocative nature of the exploration experience was manipulated by varying how frequently a yaw-rotational drift was applied to users during the exploration. We found that increases in the secondary task demand generally increased perceived levels of sickness. These deleterious effects of increased demand from secondary tasks were prominent in those experiences that weren't already highly sickening, to begin with. In scenarios where the exploration was highly sickening, the secondary task's demand had little influence on perceived levels of the affliction. Increased demand from secondary tasks was also found to reduce how well users could navigate, also worsening spatial memory. Overall, we find that increased demand from secondary tasks performed during exploration produces unfavorable effects on the VR experience.

Our findings raise several interesting follow-up questions. Would increases in the demand of positively valenced secondary tasks produce similar effects on CS? Would similar trends be observed if the higher level of STD was in between the demands of a 1-back and 2-back task? More interestingly, what is the threshold at which secondary tasks that help in reducing sickness, become exacerbatory? In future work, we wish to obtain answers to such questions. Our immediate interests, however, lie in studying the aforementioned threshold, empirically detecting quantifiable inflection points at which secondary distraction tasks reverse from being sickness-reducing to sickness-inducing.

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