Design Implications from Cybersickness and Technical Interactions in Virtual Reality

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Abstract. The present study sought to advance understanding about the relationships among contextual, individual, and technical factors in their influence upon human responses to virtual reality (VR) environments. Within this examination, the researchers first conducted a systems analysis of the two comparable VR training environments to isolate potential cybersickness antecedents. Second, a pilot study presented both environments in randomized order to participants to examine how specific features in these environments contributed to user cybersickness responses. Finally, these results were examined considering a triadic theory of cybersickness which positions the phenomenon as a combination of task, system, and individual differences converging and interacting.

Keywords: Cybersickness · Virtual reality · User experience

1 Cybersickness Resituated

1.1 Positioning Cybersickness

Researchers traditionally have grounded examinations of cybersickness (CS) firmly in the physiological realm. This is neither surprising, nor entirely ineffective, as CS is triggered by a physiological situation (interaction with a cyber system of some sort, including virtual reality VR) and resulting in symptoms akin to those experienced in simulator sickness (regardless of whether motion is virtual or real). The reigning theory firmly lies in a bias toward the physical; a mismatch between the vestibular (balance and movement) and visual senses [7] manifests with symptoms such as nausea, disorientation, headache, sweating, and eye strain (e.g. [4]).

However, this bias toward the role of the physical body and its unique perceptual mismatch may be leading researchers to overlook more nuanced interactions between the human, the technical system, and the task [2]. In this scoping of the CS problem, the boundaries of the problem are extended so that more nuanced factors can be considered as likely contributors to CS symptoms. This triadic account then can provide insight into the relationships among symptoms and individual differences, combinatorial features of hardware and software, as well as cognitive and embodied tasks within the cyber environment.

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An opportunity to examine the triadic CS model arose when two projects called for using one set of computer aided drafts to develop two different VR worlds, based on real-world oil rigs.

2 A Tale of Two Rigs

The two VR environments examined in the present study were designed from the same CAD drawings of an ADT-500 oil rig. While created from the same architectural core, the purposes of the environments were different. Rig A was designed as a multi-purpose training tool. From its inception, its end users were trainees and instructors who were the people who typically live and work in these environments. Rig B's end users were different. This environment was designed primarily to provide business personnel opportunities to conduct "walk-throughs" on a rig environment. Rig B end users navigate the space together, even if they are not co-located, and can share attention on a rig that has been labeled to assure that all users know where they are located and what they are looking at, even if they are unfamiliar with life on a rig.

As the end users required different interactions within the systems, the design decisions for Rig A varied from those for Rig B. It provides an excellent example of the inseparability between the considerations of system and task. While imperative to differentiate the rigs for these uses, these design decisions impacted the factors that are potential contributors to cyber sickness. The following section highlights some examples of design differences between these two environments, in relationship to the theoretical cybersickness factor.

2.1 Field of View

Research suggests that both internal (the virtual camera angle) and external (screen size and viewing distance) fields of view (FOVs) affect cyber sickness, but the relationship between internal FOV (iFOV) and external FOV (eFOV) is complicated [14]. Counter intuitively, congruence between eFOV and iFOV is more likely to trigger cybersickness symptoms (Fig. 1).

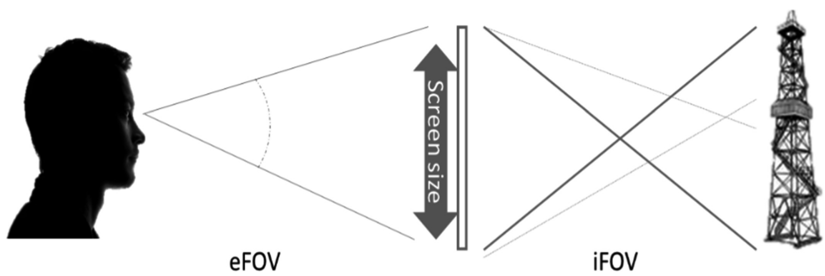


Fig. 1. eFOV provides the user access to the virtual world by externalizing the image via a display, whereas iFOV comes from the internal virtual "camera angles". Adapted from [10].

The studies by van Emmerik and colleagues [14] suggest that cybersickness symptoms may be reduced by increasing the difference between eFOV and iFOV. Further, they noted that postural stability was linked to the cybersickness symptoms, raising a concern for task-based VR contexts (as opposed to the traditional ocular-motor and gustatory symptoms raised in the SSQ).

For the Rig A and Rig B comparison, the eFOV to iFOV ratio is more pronounced in Rig B than Rig A, and consequently, Rig B introduces greater opportunity for time and attention to be given to very wide-camera angle vantages. When wearing the VR headset, the display screen is very close to the eyes yet the image upon first sight and while initial orienting is wide-angle, the exploration of the rig a priority in this environment. Simply, Rig B has a proximal eFOV: distal iFOV (see Fig. 2). Whereas the tasking assigned to Rig A holds the a stable eFOV (with the headmounted VR), but changes the camera angles with the tasks to be more frequently focused.

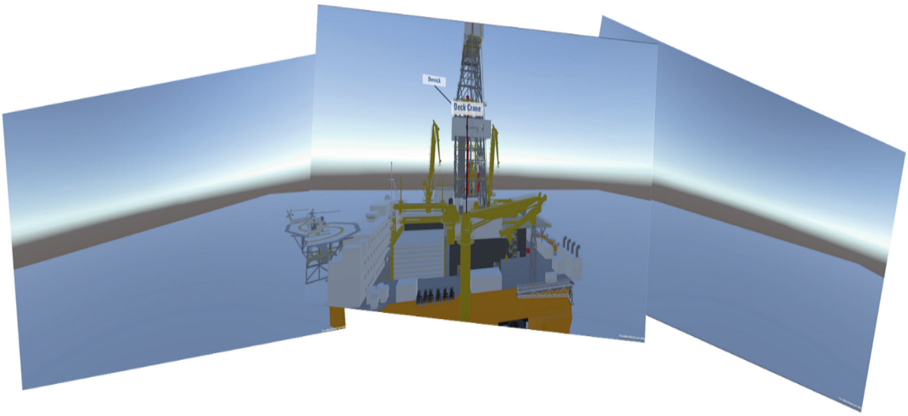


Fig. 2. Rig B example on ATD 500. iFOV overlaps with task, as users of the Rig B simulation system are more likely to engage in “exploration” compared to Rig A users.

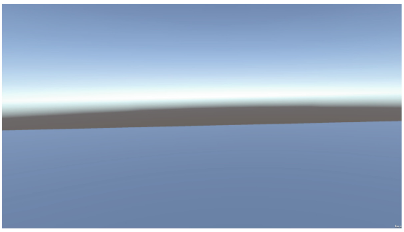
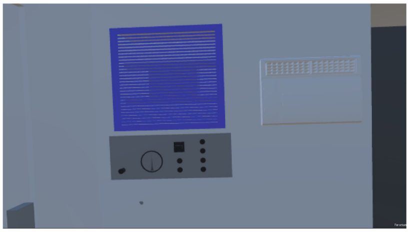
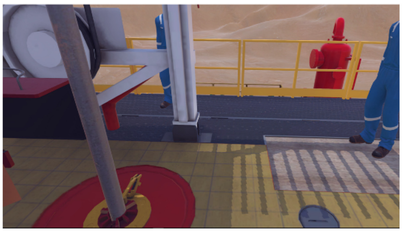
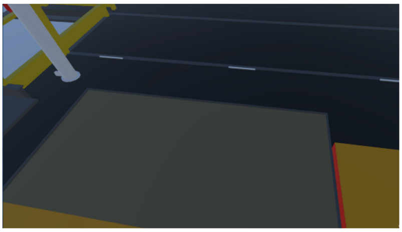
As FOV presents immediate embodiment cues for navigation, regardless of whether the affordances are embedded into the system or not, it informs the experimental design described in Sect. 3.

2.2 Level of Detail

Rig A had a much higher level of detail in range of colors and textures implemented in the simulation than Rig B. Take a look at Table 1 below for images comparing the level of detail built into Rig A and Rig B.

This difference in the level of detail throughout the simulations may also affect the susceptibility of VR environment users experiencing cybersickness symptoms. Research has shown that the more realistic a VR environment is, the more likely it is to induce cybersickness [4, 10].

Table 1. Comparison of the level of detail between Rig A and Rig B simulations.

RIG A	**RIG B**
Horizon	
	
Workroom - AC Unit	
	
Workroom - Window	
	
Workroom - Chair + Computers	
	
Drilling Floor	
	

While it may seem that increased level of detail does not align with the sensory conflict theory, it potentially follows a different aspect of sensory conflict that the results of other studies also seem to follow. A dissonance triggered by a difference between what is expected of the VR environment and what is presented in the VR environment results in cybersickness symptoms. However, some studies suggest that when the difference between what is expected and what is presented decreases, the risk of inducing more cybersickness in VR users also increases. For example, the smaller the difference between the external field of view (screen size and viewing distance) and internal field of view (the virtual camera angle), the more cybersickness VR participants experienced [14]. According to these positions on realism, when there are unrealistic elements in a VR environment, such as impractical scenarios and limitations in the VR, cybersickness may occur. As realism increases, the chance of inducing cybersickness increases.

Examples of possibly cybersickness-inducing realism within Rig A include avatars, a detailed horizon, metal texture, vibrant colors, object depth, interior fluorescent lighting, shading and casting, large windows, and suspended ceiling grates. Rig B has less realistic features, such as a flat air conditioning surface, solid color texture and shading, flat objects, and boxy doghouse wall-to-ceiling structure. Furthermore, labels are an unrealistic feature in Rig B which are absent in Rig A.

2.3 Locus of Control

Both a psycho-construct and a literal form of manipulating oneself through space, the phrase "locus of control" (LOC) can mean a bevy of things when raised for an interdisciplinary audience. In such a vein, the present work embraces this holistically and includes psychological components (the study described below includes LOC metrics) as well as manual navigation from a first-person perspective within the VR worlds. The following description highlights aspects of the control and navigation experiences within the rigs.

While walking is the same in both simulations, the method of teleportation differs. Rig A teleportation was more precise than Rig B. A teleportation line appears to indicate where a user may navigate to throughout the VR simulation. The Rig A simulation casts a blue straight teleportation line (Fig. 3) that teleports users to the exact location commanded at the end of the teleportation line (as long as it was on the ground or floor). The Rig B simulation projected a green parabolic teleportation line perpendicular to the floor, (Fig. 4). However, there are restricted areas in the simulation design preventing some of these points to correctly teleport. If the teleportation line is in a restricted area, the system defaults to another teleportation location.

The teleportation line in Rig B is less accurate than the one in Rig A because the navigation was restricted to certain areas even though the user could direct the teleportation line anywhere. Thus, the VR environment user would be teleported to an entirely different area in the simulation than expected. This is an example of sensory conflict which leads to a higher risk of experiencing cybersickness. Sensory conflict theory occurs when the VR environment and reality are perceived simultaneously. The vestibular system does not sense the motion that the visual system perceives, and thus, induces cybersickness [7].

Fig. 3. The figure illustrates the straight teleportation teleport line in the Rig A simulation. (Color figure online)

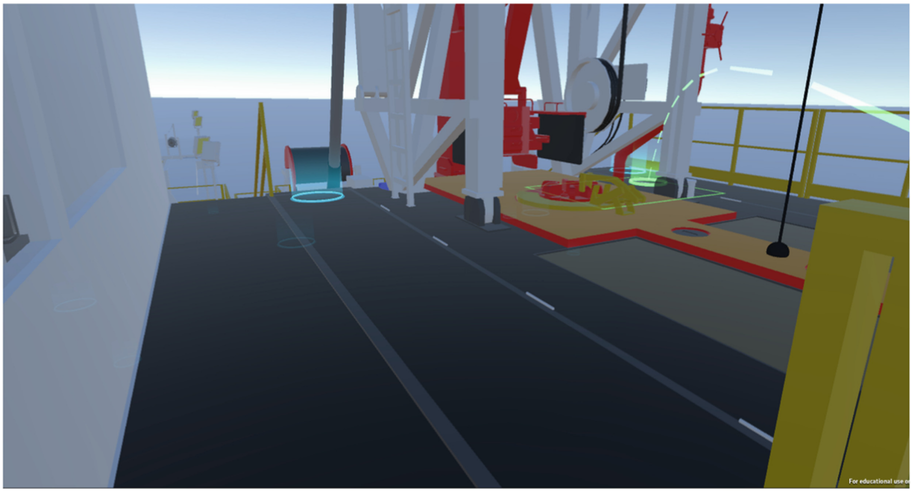


Fig. 4. The figure illustrates the parabolic teleport line in the Rig B simulation as well as the blue circles that the VR environment user can teleport to. (Color figure online)

A similar experience was examined in a study where it stated that a "mismatch between visual and vestibular cues can cause simulator sickness" [9]. For example, "as the user took one step, she was moved 10 steps in the VR environment. This causes a large mismatch between vestibular and visual cues and might be the reason for users experiencing more simulator sickness using this specific technique" [9]. The expectation of what should happen and what occurs in the VR environment is disproportionate and can cause cybersickness symptoms. This aligns with the sensory conflict theory of cybersickness which refers to the clash between the vestibular (physically senses movement from VR graphics) and visual (seeing) systems in the virtual environment [4, 7].

An early study done by Bowman, Koller, and Hodges [3] also found dissonance to relate to cybersickness symptoms when their results indicated "that motion techniques which instantly teleport users to new locations are correlated with increased user disorientation" (p. 45). This corresponds to the postural instability theory of cybersickness which occurs "whenever the environment changes in an abrupt or significant way, and where postural control strategies have not been learnt the result is postural instability" [4]. This type of change occurs in many VR environments when a visual change occurring in the VR does not match with how an individual would normally move. Instantaneous teleportation is not a natural navigation. The dissonance between normal postural control and the visual system due to "abrupt and significant" changes in the VR environment can result in cybersickness [4]. This type of change occurs in many virtual environments when a visual change occurring in the VR does not match with how an individual would normally move.

Further, it has been reported that "participants who have good control in a virtual environment can better predict future motion and are found to be less susceptible to cybersickness" [4]. Likewise, the dissonance felt when the expectation of the desired teleportation location where the VR environment user would be teleported in the SO5 simulation and where the user actually teleported to when the teleport line did not exactly match with the restricted area of teleportation is an example of dissonance of the senses in a VR environment, which can lead to cybersickness. This particular situation more closely aligns with the postural instability theory and explains why the movement in the Rig B simulation may lead to experiencing more cybersickness symptoms than movement in the Rig A simulation.

Studies on locus of control in virtual environments also observe how dissonance can lead to cybersickness. In studies on locus of control, it was found that the less control or prediction VR users had in their environment, the more cybersickness they experienced [1, 4, 8, 11]. This also aligns with the sensory conflict theory in that the mismatch between two sensory systems: visual (senses movement from VR graphics) and vestibular (senses lack of physical motion).

3 Walking in Two Worlds—A Study

To examine the impacts of these design decisions on user experiences, particularly in respect to cybersickness, participants were exposed to both VR rigs, randomized by order. They were guided in tasks by a researcher so that the time activity spent in each VR world was semi-controlled. That said, as user familiarity with gaming generally varied, as well as familiarity with this kind of environment, users were given the liberty to explore areas of the rig and take their time with navigation controls in a manner that they found comfortable.

Participants experienced two VR environments differing in level of visual detail using the HTC VIVE. The order in which the environments were presented was randomized. Participants were guided through the same 7 tasks in each environment for a total of 10 min. The total time a participant spent in each environment was recorded.

Participants were asked to complete a set of surveys administered at different points. Before experiencing the first VR environment, participants completed a personality survey and the Simulation Sickness Questionnaire (SSQ) to establish baseline cybersickness scores. The SSQ was administered after each VR experience in addition to an experience survey. After the second VR experience, participants completed the Motion Sickness Susceptibility Questionnaire (MSSQ) and a demographics survey.

The study included a total of 33 participants of which the majority (78.8%) were between the ages of 18 and 26, 12.1% were between 26 and 40, 6.1% were between 41 and 60, and one (3%) participant reported being under 18. The majority of the participants, 57.6%, were female and 42.4% were male. The average weight of participants was 162.2 lbs. with an average height of 5.6 ft. Participants' familiarity with VR headsets was very minimal as only one participant owned a device and the majority of participants (36.4%) indicated having used one once or twice. Participants' experience playing video games was also minimal; 54.5% reported rarely playing video games. With regard to participants' vision, 63% wore corrected lenses and 33% reported having an astigmatism.

3.1 Physiology of Pupillary Distance

While recent work suggests that eye position itself cannot account for ocular strain and associated symptoms in cyber contexts [13], there has been some push for more consideration of pupillary distance (PD) coming from some industry partners. While the push may be in part informed by necessary consideration of multiple genders and ethnicities in design, the empirical support for the role of PD in cybersickness experiences is debatable. Consequently, it was important for the present study to include this basic physiological consideration. The Pupillary distance (PD) of the participants ranged from 53 to 69. The majority of the participants (27.3%) had a PD of 62. The PD of the participants averaged 61.91 (M = 61.91), the SD = 3.2, and SE = .558.

Of the 33 participants:

27.3% (n = 9) had a PD of 62
15.2% (n = 5) had a PD of 64
12.1% (n = 4) had a PD of 63
9.1% (n = 3) had a PD of 61 and 9.1% (n = 3) a PD of 65
6.1% (n = 2) had a PD of 58 and 6.1% (n = 2) a PD of 60
3% (n = 1) had a PD of 53, 3% (n = 1) had a PD of 54, 3% (n = 1) had a PD of 57, 3% (n = 1) had a PD of 66, and 3% (n = 1) had a PD of 69

The PD data was divided into three groups to create low, medium, and high PD groups. The group ranges were as follows:

Low PD**:** PD is between 53 and 57
Medium PD**:** PD is between 58 and 62
High PD**:** PD is between 63 and 69

The majority of the participants (48.5%) had medium PDs with the least amount of participants in the low PD category (9.1%).

3.2 The Experience of Simulation Sickness Between Conditions

To understand the effect of condition on participant report of sickness, regardless of order, researchers examined the overall scores reported in the SSQs. Overall, most participants did not experience cybersickness symptoms in any of the conditions (a baseline survey to ascertain initial symptom rates, Rig A, and Rig B). At baseline, 84.8% (n = 28) of participants did not experience general discomfort and 12.1% (n = 4) experienced slight general discomfort. The same percent, 84.8% (n = 28) of participants did not experience general discomfort in the Rig A simulation, and 15.2% (n = 5) experienced slight general discomfort. After Rig B, 90.9% (n = 30) of participants did not experience general discomfort and 9.1% (n = 3) experienced slight general discomfort.

This section presents analyses for determining if there are any differences in individuals' experienced simulation sickness symptoms following baseline, Rig A, and Rig B. First, normality was tested to determine the appropriate statistical analysis test to use. This procedure and results are presented here. To account for change scores in this within-measures design, scores were calculated for nausea, disorientation, oculomotor, and total SSQ score. A Mixed Design ANOVA was run to determine if there are any differences in simulation sickness scores depending on the order of condition.

For both condition orders (Rig A first and Rig B first), the overall nausea simulation sickness scores were on average lower at baseline (mean = 3.58), and equal for Rig A and Rig B (mean = 5.37). The average nausea score for individuals who experienced Rig B first (mean = 5.09) was higher at baseline than those who experienced Rig A first (mean = 2.24). For the experience of nausea symptoms in Rig A, the average nausea score for individuals who experienced Rig B first (mean = 6.36) is higher than those who experienced Rig A first (mean = 4.49). For the experience of nausea symptoms in Rig B, the average nausea score for individuals who experienced Rig A first (mean = 5.61) is higher than those who experienced Rig B first (mean = 5.08).

In sum, the participants in the present study reported more nausea simulation sickness symptoms after their second exposure to the simulation regardless of the order in which condition was experienced. This aligns with postulations regarding cybersickness, simulator sickness, and other maladies in connection with time-in-system/exposure rates. However, these values represent trends. There was no significant effect of condition on the experience of nausea symptoms. In other words, there are no significant changes in the experience of nausea symptoms between conditions (baseline, Rig A, and Rig B); $F(2,60) = 1.294$, $p = .282$, np2 = .041. Further, there was no significant interaction between condition and condition order in terms of nausea scores. There are no differences in nausea scores between conditions and nausea scores are the same for each condition order; $F(2,60) = .982$, $p = .380$, np2 = .032. Thus, regardless of condition order, there is no difference in the experience of nausea symptoms between conditions. A two-way mixed ANOVA showed that there was no significant main effect of condition on nausea simulation sickness scores. Again, while not statistically significant, participants reported more nausea simulation sickness symptoms when their second simulation was Rig A.

To better understand condition on ocular-motor symptoms, a mixed-design ANOVA was also conducted. For both condition orders (Rig A first and Rig B first), the overall oculomotor simulation sickness scores are on average lower at baseline (mean = 6.12), and higher for Rig A (mean = 9.71) than for Rig B (mean = 7.58). The average oculomotor score for individuals who experienced Rig B first (mean = 6.70) is higher at baseline than those who experienced Rig A first (mean = 5.80). For the experience of oculomotor symptoms in Rig A, the average oculomotor score for individuals who experienced Rig B first (mean = 9.10) is lower than those who experienced Rig A first (mean = 10.26). For the experience of oculomotor symptoms in Rig B, the average oculomotor score for individuals who experienced Rig A first (mean = 8.03) is higher than those who experienced Rig B first (mean = 7.07).

As with the nausea symptoms, individuals reported more oculomotor symptoms after having experienced Rig A, regardless of condition order. The same tests were conducted statistically, and these appear to be trends and did not reach significant oculomotor symptoms between conditions (baseline, Rig A, and Rig B); F (1.5,45) = 1.715, *p* = .197, np2 = .054.

These symptom trends feed specifically into results regarding disorientation, particularly considering the relationship between the human interactions within the systems and the artistic designs for the system navigations. For individuals that experienced Rig A first, the disorientation scores are the same, on average, after experiencing both Rig A and Rig B (mean = 5.73).

For individuals that experienced Rig B first, the disorientation scores are higher, on average, after experiencing Rig A (mean = 13.92) than after Rig B (mean = 8.35).

Disorientation scores were lower on average for Rig B (mean = 7.04) than Rig A (mean = 9.83). These results suggest that individuals reported more disorientation symptoms after each condition if they experienced Rig B first. The reported disorientation symptoms increase drastically after having experienced Rig A second. A two-way mixed ANOVA showed that there was a significant main effect of condition on disorientation simulation sickness scores (F (1.6,46.59) = 5.041, p = .016, np2 = .144) with scores lower on average at baseline (mean = 1.86) than for Rig A (mean = 9.83) and Rig B (mean = 7.04). Additionally, there was no significant main effect of condition order on disorientation simulation sickness scores (F (1,30) = 1.709, p = .201, np2 = .054) with overall scores lower on average at baseline (mean = 1.74) than Rig A (mean = 9.57) and Rig B (mean = 6.96). Furthermore, there was also no significant interaction between condition and condition order F (1,30) = 1.709, p = .201, np2 = .054). The findings indicate that the experience of disorientation symptoms differ between conditions with individuals having experienced more disorientation in Rig A than any other condition. Furthermore, results indicate that condition order has no effect on the experience of disorientation simulation sickness symptoms in the different conditions.

3.3 Individual Differences and Psychometric Responses

Participants were asked to indicate via Likert-style survey aspects of their experiences following interactions in each condition. When asked to indicate the degree to which they found the navigation easy to use, the majority of participants (54.5%) felt very positive/good about the ease of navigation in Rig A. Individuals' satisfaction with ease of navigation was slightly lower in Rig B with 42.4% feeling very positive/good about the ease of navigation. They were also more likely to feel "very positive/good" looking at objects in Rig A (66.7%) than Rig B (54.5%), although it should be noted that no one indicated feeling negatively about looking at objects in either environment. It was of no surprise that interacting with objects garnered more positive responses in Rig A vs. Rig B (Table 2).

Table 2. Participant opinions of interactions with objects in Rigs A & B.

	Rig A		Rig B	
	Frequency	Percent	Frequency	Percent
Feel generally negative	2	6.1	3	9.1
Feel neither negative nor positive	4	12.1	10	30.3
Feel generally positive	14	42.4	10	30.3
Feel very positive/good	13	39.4	10	30.3
Total	33	100.0	33	100.0

One of the most intriguing results from the user experience survey was in regard to participant self-reported "interest" in the world (Table 3).

Table 3. Participant opinions of their interest in Rigs A & B.

	Rig A		Rig B	
	Frequency	Percent	Frequency	Percent
Feel generally negative	3	9.1	3	9.1
Feel neither negative nor positive	1	3.0	5	15.2
Feel generally positive	8	24.2	13	39.4
Feel very positive/good	21	63.6	12	36.4
Total	33	100.0	33	100.0

While an equal number of participants felt a general negative interest, the strongly "very positive/good" response was 27% higher in Rig A.

4 Discussion

There are numerous limitations to be considered in this study. First, the small sample size and use of student-body samples skewing in favor of gaming familiarity, and non-normalized data sets creates the standard cautions for generalization, especially when making assumptions about physio-sensory systems. Additionally, the data collected was non-normal and the ANOVA for examining effects by condition could not be evaluated. Beyond these obvious caveats, the research team also sees challenges in the following considerations, and offer them in the form of question for future VR design:

(1) Inherent sexism in design of hardware (e.g. rigid pupillary distance in headgear, uncomfortable coronal fit) may contribute to cybersickness physiological responses, what task-based design decisions may also be contributing to biases within whole system and consequently introducing risk?
(2) When task design influences artistic decisions which may contribute to cybersickness, how does that feedback into compensatory processes for hardware/software development in parallel?
(3) How can the industry contribute to authentic metrics for predicting the likelihood of cybersickness symptoms based on the triadic influence of system, task, and individual factors (as opposed to the reactive and diagnostic measures currently standard practice)?

The present study in its limited design barely scratches the surface of these larger questions. However, the hope is to position this work a part of a scholarly dialog to advance safer VR tools.

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