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ORIGINAL ARTICLE

Evaluating discrete viewpoint control to reduce cybersickness in virtual reality

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Abstract
Cybersickness in virtual reality (VR) is an ongoing problem, despite recent advances in head-mounted displays (HMDs). Discrete viewpoint control techniques have been recently used by some VR developers to combat cybersickness. Discrete viewpoint techniques rely on reducing optic flow via inconsistent displacement, to reduce cybersickness when using stationary HMD-based VR systems. However, reports of their effectiveness are mostly anecdotal. We experimentally evaluate two discrete movement techniques; we refer to as rotation snapping and translation snapping. We conducted two experiments measuring participant cybersickness levels via the widely used simulator sickness questionnaire (SSQ), as well as user-reported levels of nausea, presence, and objective error rates. Our results indicate that both rotation snapping and translation snapping significantly reduced SSQ by 40% for rotational viewpoint movement, and 50% for translational viewpoint movement. They also reduced participant nausea levels, especially with longer VR exposure. Presence levels, error rates, and performance were not significantly affected by either technique.

Keywords Virtual reality · Vection · Cybersickness · Visually induced motion sickness

1 Introduction

Low-cost head-mounted displays (HMDs) and tracking solutions have made virtual reality (VR) more accessible than ever. VR has long been used in many application areas such as health care, entertainment, and scientific visualization (LaViola 2000; Bowman and Mcmahan 2007). Game companies are developing VR versions of console and PC games, such as Serious Sam VR (developed by Croteam[1]) and Resident Evil 7 (developed by CAPCOM[2]). The most notable benefit of VR is its immersive quality, which helps induce a sense of presence—the psychological phenomenon of feeling as though you are in the virtual place (Sanchez-Vives and Slater 2005).

Due to the recent widespread adoption of VR, the long-standing problem of *cybersickness* is an increasingly important issue (LaViola 2000; Davis et al. 2014). This is due, in part, to the potentially long VR exposures gamers may be willing to subject themselves to experience this new form of gaming. Moreover, controller-based virtual movement (e.g., via a joystick) while the user is stationary is commonly used in games. Yet, this mismatches virtual and physical motion; as will be discussed in depth below, such mismatches yield notably worse cybersickness than walking systems (e.g., the HTC Vive).

Hardware improvements have reduced the impact of several technical factors that contribute to cybersickness, such as latency and jitter (LaViola 2000; Davis et al. 2014). Also, HMDs that support large-scale tracking areas, such as the HTC Vive, allow users to walk naturally, further reducing cybersickness. However, stationary VR setups (e.g., Oculus Rift) are still common, as they offer several benefits over walking systems, for example, lower cost and smaller space requirements. Cybersickness limits training effectiveness in simulators and may have negative effects on performance and learning. For example, flight simulator users may

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minimize head movement to avoid cybersickness, but this, in turn, yields poor training transfer to real situations (Hettinger et al. 1990).

VR game developers have used several techniques (Dorado and Figueroa 2014; Fernandes and Feiner 2016; Weißker et al. 2018) to combat cybersickness in stationary VR setups. We evaluate the effectiveness of a new class of cybersickness reducing techniques that rely on discrete movement. Such techniques have recently been used in some VR games. We refer to the techniques as rotation snapping (RS) and translation snapping (TS).

Rotation snapping operates by eliminating frames during viewpoint rotation; in other words, the rotation becomes discrete as the viewpoint snaps. Viewpoint motion from head-tracking is excluded since it yields consistent visual and vestibular information. This technique can be employed while moving a mouse or other input device (e.g., joystick) that does not yield correct vestibular cues. The effect of rotation snapping is seen in Fig. 1.

Translation snapping is similar to *rotation snapping*, using discrete movement (short jumps) for translational displacement, during both forward and backward movement (see Fig. 2). The premise of both techniques is to reduce optical flow and inhibit vection (the illusion of self-motion) by employing discrete movement (Seno et al. 2011), i.e., reducing continuous viewpoint motion by skipping frames. This technique also can be employed while moving a mouse or other input device (e.g., joystick).

These techniques are easy to implement at a low cost and are thus potentially attractive for developers. The techniques can be applied in setups with limited tracking space prohibiting natural movement, and potentially even for users incapable of walking (Fernandes and Feiner 2016). Through noncontinuous viewpoint motion, users may experience lower levels of cybersickness and hence can potentially use VR systems for longer periods. This could help them acclimatize to VR through repeated exposure. The techniques could also be a good secondary interaction method for use in comfort mode in many VR applications and games. We developed and evaluated both techniques using a stationary HMD-based VR setup; they could potentially be applied in other hardware environments as well, but this is beyond the scope of the current research.

Other researchers (Ryge et al. 2018) have called similar approaches discrete viewpoint control (a more general term we also employ). Game developers have employed similar techniques such as comfort mode (e.g., *Serious Sam VR*) or discontinuous rotation (e.g., *Resident Evil 7*). There is anecdotal evidence of the effectiveness of these techniques; we present controlled experiments evaluating their effectiveness at reducing cybersickness for both viewpoint rotation and translation. However, despite the expected benefits, we also

Fig. 1 Top row of images shows a standard (non-snapping (NS)) viewpoint rotation. The second row shows the same rotation with our rotation snapping technique enabled. A fast transition eliminates the intermediate frames, meaning the rotation becomes discrete

Fig. 2 Top row of images shows a standard (non-snapping) translation. The second row shows the same movement with translation snapping. A jump movement eliminates intermediate frames, meaning the translation becomes discrete, similar to a short-range teleport

hypothesize that discrete viewpoint control may negatively affect user performance and presence due to noncontinuous motion and "strain caused by the visual 'jumps,' which also resulted in breaking the users' immersion" (Boletsis and Cedergren 2019). We also note that there are potential spatial updating implications of employing such techniques. After all, the illusion of VR relies on accurately simulating the human perceptual system; discrete movement actively breaks this model.

The operational parameters (e.g., snapping range, speed, etc.) of both techniques were developed based on the results of preliminary experiments presented here. In addition, we ran two formal experiments to evaluate the effectiveness of each technique at reducing cybersickness. Our results show that overall these techniques do reduce cybersickness with little impact on user preference and performance. This article extends our previous research on discrete rotational movement (Farmani and Teather 2018). In the previous research, we confirmed the effectiveness of rotational discrete motion at reducing cybersickness. We previously referred to this technique as *viewpoint snapping*, but now refer to it (more precisely) as *rotation snapping*. In this research, we additionally investigate *translation snapping* in VR during translational movement while using stationary VR setups.

2 Related work

2.1 Cybersickness: causes and measurements

Cybersickness is a common side effect of video games, virtual reality systems, and driving simulators (LaViola 2000). Cybersickness presents a variety of symptoms, such as nausea, headache, pallor, sweating, dry mouth, heavy-headedness, disorientation, vertigo, ataxia, and in extreme cases, vomiting (Stanney and Kennedy 1997; LaViola 2000). We briefly discuss some factors that influence cybersickness, but the interested reader is encouraged to see a more comprehensive survey of the topic such as (Davis et al. 2014; Rebenitsch and Owen 2016)

Cybersickness occurs when the visual system perceives self-motion, while the vestibular system indicates that the body is stationary with respect to gravity and position (Hettinger et al. 1990). This illusion of self-motion is also called vection (Hettinger et al. 1990; So et al. 2001), which Tschermak (1931) defines as a "powerful illusion of self-motion induced by viewing optical flow patterns." A variety of factors contribute to cybersickness (Kolasinski and Gilson 1998). Some of these include individual factors, such as user age and gender (Arns and Cerney 2005; Park et al. 2006, 2014). Technological factors, like display refresh rate and latency (Kolasinski and Gilson 1998), field of view (Seay et al. 2002; Toet et al. 2008) and even visual realism of the environment (Davis et al. 2015), have been shown to influence cybersickness. Also, task factors such as movement direction (Stanney and Kennedy 1997; Yao et al. 2016) and consistency of movement speed (Bonato et al. 2008) also play a role. Notably, previous work (Kemeny et al. 2017) has shown that rotational movement yields greater sickness levels compared to translation movements. Davis et al. (2014) present a comprehensive overview of the causes of cybersickness.

Previous studies (Hettinger and Riccio 1992; Kennedy et al. 1996) have shown that cybersickness is significantly affected by movement speed and does not necessarily continuously increase with rotation speed. For example, Hu et al. (1999) conducted a study using an optokinetic drum with black and white stripes, where they varied circular vection speed from 15°/s to 90°/s. Their results indicate that as rotational speed increased, symptoms of induced vection, including simulator sickness, increased, peaked, and then declined, with peak symptoms occurring at a rotation speed of 60°/s. This result indicates that vection and simulator sickness increase to a point, then stabilize. They also suggest that at a rotational speed of 200°/s, the viewer no longer experiences vection. So et al. (2001) report that the time for vection to occur is reduced for speed changes from 3 to 10 m/s. After 10 m/s it stabilizes.

The most widely employed method of quantifying cybersickness is the simulator sickness questionnaire (SSQ) (Kennedy et al. 1993; Stanney and Kennedy 1997; Davis et al. 2014). We use the SSQ in our experiments, as well as subjective nausea scores queried at regular intervals. The SSQ was validated by Kennedy et al. (1993) and is based on three categories: oculomotor factors (e.g., eyestrain, difficulty focusing, blurred vision, and headache), disorientation factors (e.g., dizziness and vertigo), and nausea factors (e.g., stomach awareness, increased salivation, and burping). Total SSQ scores are obtained by ranking each of the 16 items on a 4-point Likert scale, then summing each of the three sub-components. Total SSQ is then calculated as (Nausea Score) + (Oculomotor Score) + (Disorientation Score) × 3.74 (Kennedy et al. 1993).

2.2 Techniques to reduce cybersickness

Several researchers have proposed different approaches to reduce cybersickness during rotation and translation (Chang et al. 2013b; Dorado and Figueroa 2014; Fernandes and Feiner 2016; Kemeny et al. 2017). One approach involves adding a depth of field blur effect during rotation, which simulates focusing the eyes at a different depth, blurring blurs parts of the scene slightly (Budhiraja et al. 2017). While this did not significantly decrease cybersickness, it did delay cybersickness onset by 2 min.

The “headlock” technique (Kemeny et al. 2017) temporarily disables viewpoint movement during rotation. The authors report that headlock significantly reduced cybersickness during rotation by 30% compared to joystick rotation (Kemeny et al. 2017). However, a presence questionnaire revealed that the technique also significantly reduced user presence, and participants reported that headlock was not intuitive. We also note that both the headlock and rotation blurring techniques only work during rotation; the authors did not propose solutions for translation.

Perhaps the most commonly applied technique in commercial games (e.g., *Serious Sam VR*) involves reducing the field of view during movement (Fernandes and Feiner 2016). This technique is sometimes referred to as “tunneling.” Fernandes and Feiner (2016) report that tunneling slightly—but not significantly—reduced total SSQ scores. However, raw discomfort scores suggested a reduction in nausea with tunneling, but FOV reduction can potentially affect user performance in other ways.

Other authors have looked at methods to modify user movement in VR to combat cybersickness. Previous work has shown that changing vection speed and direction yields more severe sickness than steady, consistent, vection caused by walking or turning at constant speeds/directions (Bonato et al. 2008). Noting this, Dorado and Figueroa (2014) proposed using ramps instead of stairs, arguing that ramps produce more steady motion than stairs. They report that using ramps significantly reduced total SSQ scores by as much as 24% in two user studies (Dorado and Figueroa 2014). Presence and performance were not measured, and it is dependent on task and scenario.

Other researchers proposed reducing cybersickness by increasing the sense of embodiment and reducing vection. Chang et al. (2013b) proposed using rest frame to reduce cybersickness (e.g., displaying a cockpit) which “delayed the onset of cybersickness by alleviating users’ attention or perception load.” Similarly, using a virtual nose or adding a user avatar can also reduce cybersickness (Hecht 2016). Using rest frames in a roller coaster as Chang et al. (2013b) suggested also significantly reduced total SSQ by around 10%.

A limitation of several recent studies (Chang et al. 2013b; Fernandes and Feiner 2016; Budhiraja et al. 2017) is that most focused *exclusively* on evaluating the effectiveness of cybersickness reduction techniques at reducing cybersickness, without simultaneously considering the potential impact on user task performance. We speculate that some of these techniques may impact user performance and/or presence. For example, reducing the FOV (Fernandes and Feiner 2016; Rebenitsch and Owen 2016) cuts out parts of the user’s view; in a fast-paced action game, this could prevent the user from seeing an enemy, and thus may impact their ability to react to game events as quickly. Similarly, adding UI elements like cockpits, rest frames, or even a virtual nose occlude parts of the screen. Finally, some of these techniques (e.g., using a cockpit) do not generalize well. For instance, a vehicle or spaceship could be used in a game like Valkyrie,[3] but in a game like Valiant,[4] a kettle hat should be added to the first-person view instead. Neither approach is appropriate for a VR medical training simulator. Many existing techniques either have limitations preventing widespread adoption or potentially impact other important aspects of VR usage (e.g., task performance and presence).

2.3 Discrete movement

Discrete movement reduces or inhibits vection (Seno et al. 2011), and is a good candidate for further study in reducing cybersickness. There is anecdotal evidence of the effectiveness of discrete movements from industry. For example, the games *Serious Sam VR* and Capcom’s *Resident Evil 7* both include a “snap rotation” feature. When activated, this option prevents the player from rotating their viewpoint continuously, instead snapping their rotation to fixed increments. Mark Scharamm of VR-Bits[5] used a similar approach for a travel technique he called “Cloud Step.”[6] However, there are relatively few formal studies on the effectiveness of discrete movement techniques in reducing cybersickness and their effect on performance. In a previous study, we evaluated rotational discrete movement to reduce cybersickness in VR (Farmani and Teather 2018) and evaluated a technique we refer to as rotation snapping. Translation snapping is similar to teleporting, with short and constant jump distances. Weißker et al. (2018) proposed jumping to different locations each incrementally closer to the destination. Trigger walking is also similar and uses individual button presses to move the user forward one increment at a time (Sarupuri et al. 2017).

Inconsistent locomotion techniques (Seno et al. 2011) inhibit vection by reducing optical flow. In contrast, techniques like FOV reduction instead reduce optical flow by decreasing the visible imagery (Fernandes and Feiner 2016), rather than skipping imagery entirely. However, there are no “obvious” operational parameters to use for discrete motion techniques. For example, what snapping distance/angle should be used? At what speed should such techniques work? The Oculus Best Practice Guide (Yao et al. 2016) proposes a 30° snapping increment for discrete rotation; but, the reason for proposing this number is not clear, and likely determined informally via ad hoc testing.

[3] https://gaming.youtube.com/game/UCs9XYBocLgnrQIuWKf0zuCw.

[4] https://store.steampowered.com/app/344180/Valiant/.

[5] http://www.vr-bits.com/.

[6] https://www.youtube.com/watch?v=vVVdoquKhO8&t=15s.

We present a formal study of discrete motion techniques for reducing cybersickness in a series of experiments. To first determine operational parameters for our discrete movement techniques, we ran two preliminary user studies. These studies were intended to provide parameters within which to operate the techniques. In the case of rotation snapping, this is based on the camera rotation speed. In the case of translation snapping, our goal was to determine the optimal jumping distance. We then conducted two evaluations of the techniques developed. We evaluated discrete viewpoint control in a VR first-person shooter game, as well as in a path integration task, looking at both user presence and performance in the prescribed tasks.

3 Experiment 1: rotation snapping

We first present a preliminary experiment to "calibrate" our rotation snapping technique (Sect. 3.1), followed by a formal experiment assessing the effectiveness of rotation snapping to reduce cybersickness (Sect. 3.2). Its impact on user performance was assessed, as were subjective measures of cybersickness levels and presence. Two groups of participants were compared in a between-subject design: one that experienced rotation snapping (RS), and a control condition group with no snapping (NS). We first present a preliminary experiment designed to determine thresholds to active rotation snapping based on camera speed and user comfort. We then describe the rotation snapping mechanism and evaluation in detail.

3.1 Preliminary experiment

This experiment was designed to establish an approximate rotation speed threshold within which to activate our rotation snapping, and how far to snap, essentially calibrating the rotation snapping technique. Since snapping (discrete movement) may break presence (Boletsis and Cedergren 2019), our objective was to only activate snapping in situations that might lead to cybersickness, i.e., above a certain viewpoint rotation speed. We did this by determining the user-preferred speed and discomfort levels using a nausea questionnaire similar to previous researches (So et al. 2001; Fernandes and Feiner 2016) to find rotation threshold. It should be noted that the effectiveness of rotation snapping at reducing cybersickness—using these operational parameters—is then evaluated experimentally in Sect. 3.2.

3.1.1 Participants

We recruited twelve participants (university students) between the ages of 19 to 35 (Mean 24.6)—four females and eight males. They completed a pre-SSQ questionnaire to ensure that they did not present any cybersickness symptoms before the study. No symptoms were reported. Participants were not compensated.

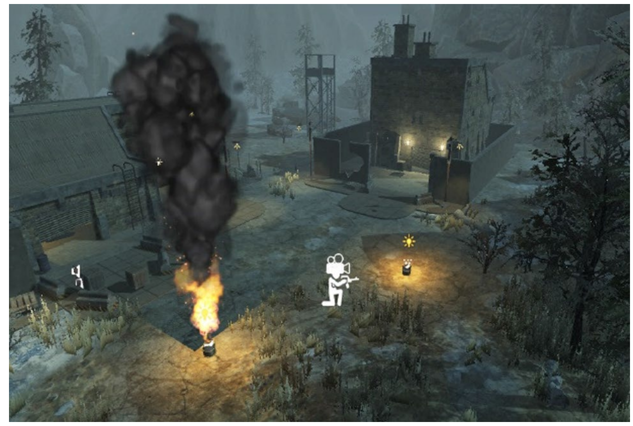

Fig. 3 Software setup environment. The FPS camera is in the center to give users a good range of rotation for visual search, the player only experiences circular movement not linear. Original environment available from https://www.assetstore.unity3d.com/en/#!/content/59359

3.1.2 Apparatus

The experiment was conducted using a PC (i5-6500 3.2 GHz CPU 3.2, GeForce GTX 970 GPU, 8 GB RAM) with an Oculus Rift CV1 head-mounted display. The software was developed in Unity and used a publicly available FPS level demo (see Fig. 3) as a base. The software automatically rotated the viewpoint continuously after the onset of the experiment, at a speed controlled by the experimenter.

3.1.3 Procedure

Participants signed a consent form and were briefed on the task. Each trial consisted of 1.2 min of exposure to a specific rotation speed. The objective was to determine at which rotational speeds participants experienced the most nausea. Participants were instructed that they could stop the experiment at any time, especially if they experienced extreme symptoms. The participant then put on the Oculus Rift head-mounted display. The camera started rotating while the participant looked forward; during rotation, they were instructed to remain stationary. They experienced 11 different speeds of rotation from lowest to highest. Every 1.2 min (i.e., at the end of each condition), the nausea rating questionnaire (Fig. 4) appeared on the screen. Participants used an Oculus Touch controller to point a ray at the intended icon to indicate their nausea level on a 10-point scale, like previous work (So et al. 2001; Fernandes and Feiner

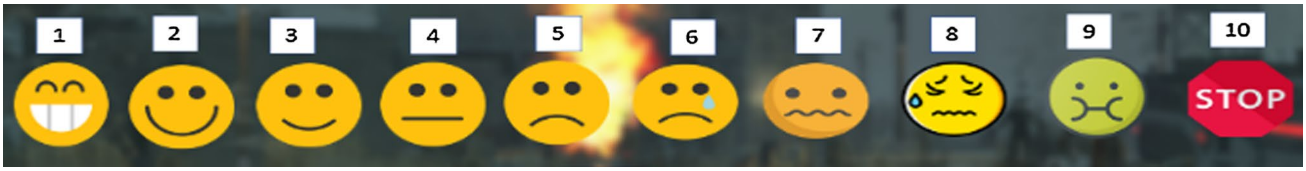

Fig. 4 Nausea scale questionnaire. Participants used this to rank their current nausea level every 1.2 min in the preliminary study, and every 2 min in the evaluation of rotation snapping

2016). Selecting a nausea score of "10" indicated that they wanted to stop and withdraw from the experiment. During the experiment, participants were also asked if they felt like they were rotating or not. Upon completion of the experiment, we asked them which rotation speed they preferred the most. The study approximately took 30 min (13 min of exposure time).

3.1.4 Design

The experiment included a single within-subjects independent variable, rotation speed, with 11 levels: 5°/s, 10°/s, 15°/s, 20°/s, 25°/s, 30°/s, 40°/s, 60°/s, 100°/s, 120°/s, and 200°/s. We note a limitation of this experiment is that we did not counterbalance rotation speed order. However, we argue that counterbalancing the rotation speed order would yield a different limitation: Some participants would be exposed to high rotation speeds immediately upon starting the experiment, yielding cybersickness right at the onset. We believe that this trade-off is acceptable and that the results of this study will still be useful in "calibrating" our rotation snapping technique. Nevertheless, a between-subjects design would likely provide better results.

The dependent variable was the average level of nausea, as reported by participants using a nausea questionnaire (Fig. 4). We also interviewed participants after the study about the most preferred speed.

3.1.5 Results and discussion

As expected based on previous work (So et al. 2001), higher rotation speeds yielded higher nausea scores (Fig. 5 and Table 1). While expected, this data provide thresholds where cybersickness was worst to help inform the design of the rotation snapping technique. Based on these findings and previous work (So et al. 2001), the preferred rotation speed was between 15 and 35°/s (chosen by 10 participants). At higher rotation speeds, participants felt uncomfortable. One-way ANOVA revealed a significant difference in nausea scores by rotation speed ($F_{10,121} = 5.1$, $p = 0.0001$).

Based on these results, a threshold of 25°/s was deemed appropriate to activate rotation snapping (Fig. 5). This threshold corresponded to the average rotation speed

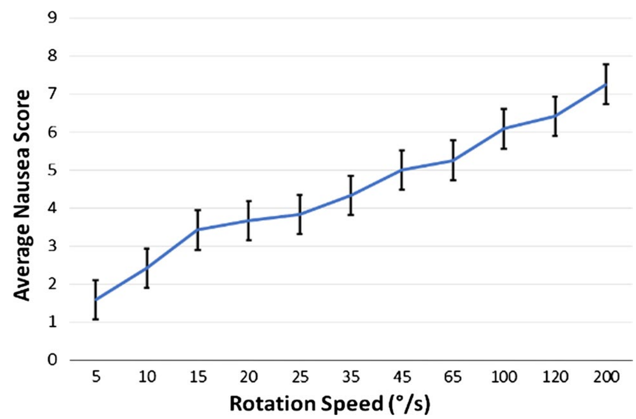

Fig. 5 Average nausea rating based on different speeds. Error bars show ± 1 SE

Table 1 Experiment one—nausea scores by rotational speed (color table online)

	Rotation Speed (°/s)									
ID/speed	**10**	**15**	**20**	**25**	**35**	**45**	**65**	**100**	**120**	**200**
P2	1	1	1	1	1	1	1	1	1	1
P8	1	1	1	1	1	1	1	1	1	1
P6	2	1	2	1	1	3	3	4	4	6
P12	1	2	2	2	2	2	3	3	3	8
P11	1	1	3	4	5	5	3	5	7	8
P1	3	4	4	4	4	5	5	5	5	5
P5	5	3	2	2	3	6	7	7	8	8
P3	5	6	6	5	6	6	7	8	9	
P7	2	5	6	7	8	7	8	9	9	
P4	4	5	6	6	6	8	8			
P9	3	4	5	6	7	8	8			
P10	1	8	6	7	8	8	9			

The red square indicates when participants withdrew from the study. It usually occurred at rotations speed higher than 65°/s. Three participants withdrew at the rotation speed of 100°/s and two at 200°/s. These are depicted as red cells in the table

where nausea scores started becoming more notable: a score of "4" on the 10-point scale. This was followed by a steady increase in average nausea scores (Fig. 5). As given in Table 1, the majority of participants still reported a nausea score lower than 4 at a rotation speed of 25°/s.

As mentioned above, there is a possible confound in this experiment, since rotation speed was always presented in the

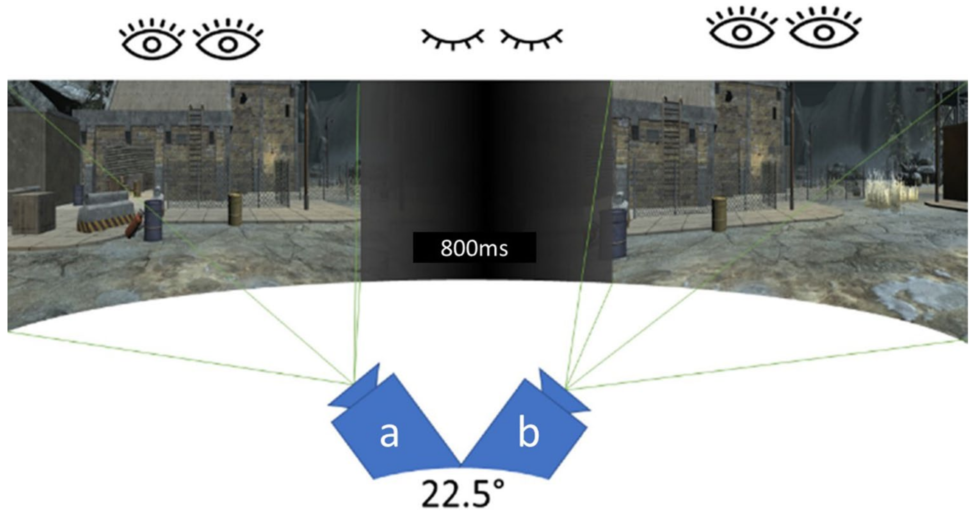

Fig. 6 Rotation snapping. **a** Current position of the camera, **b** camera position, after 22.5° snap to the next viewpoint. The closed eyes image indicates the fading transition, during which, the screen darkens

same order, and hence increased with exposure time: It is unclear if participants increasing nausea was from rotation speed or exposure. Overall, this suggests that a threshold of 25°/s may be activated at a slightly slower speed than necessary, which is unlikely to influence cybersickness but may slightly affect performance and presence. Given the range of the nausea scores (Fig. 5 and Table 1), the best answer is likely to "calibrate" a rotation snapping threshold on a per-user basis. This was not practical for the current study but may be investigated in the future.

3.2 Formal study 1: evaluation of rotation snapping

In this section, we first describe our rotation snapping technique itself, then an experiment evaluating its effectiveness. For the experiment, we used a mouse to control viewpoint rotation. Input devices like the mouse or joysticks induce cybersickness due to visual-vestibular conflicts (Keshavarz et al. 2015). As discussed earlier, cybersickness tends to be stronger in the absence of actual physical movements (Davis et al. 2014). The current study employed a mouse rather than a joystick since it is more familiar to participants and allows higher-speed position-control rotations, rather than the velocity-control rotations supported by joysticks, yielding superior navigation speed (Farmani and Teather 2018). However, we expect the rotation snapping technique to work well with either input device.

For this experiment, rotation snapping was only employed on the vertical-axis rotation (i.e., yaw). Thus, snapping only occurred when the user was turning right or left and with rotation speed over the 25°/s threshold, as determined in the preliminary experiment (see Sect. 3.1). At rotational speeds below 25°/s, the mouse produced smooth continuous viewpoint rotation. However, upon rotating above 25°/s, the continuous rotation was replaced with a fast (~800 ms) fading transition, snapping the viewpoint by 22.5° increments. The fading transition was intended to help prevent loss of spatial context by preventing immediate jumps between viewpoint thresholds. As seen in Fig. 6, this effect behaves as though the user closed their eyes, quickly turned their head 22.5°, and then opened their eyes.

We decided on a 22.5° increment for snapping based on informal pilot testing in the laboratory.[7] We initially tried a snapping distance of 45° and 30°, but pilot participants found them disorienting. We ultimately settled on 22.5° as pilot participants found it most comfortable. The snapping range is likely dependent on rotation speed and is a topic for future study.

3.2.1 Participants

We recruited 28 participants, aged 18 to 35 years old (mean age 26.4, 17 male). Participants were divided into two groups. The first group (9 males, 5 female) experienced the rotation snapping (RS) condition, while the second group (8 male, 6 female) experienced the no snapping (NS) condition. All participants had normal or corrected-to-normal vision. Participants who wore glasses keep their glasses on.

Participants had a wide range of experience with HMD VR systems: 6 participants had never used a VR system before, while 3 participants used VR frequently (1 to 6 times per week). Of the remaining participants, 5 had used VR between 1 to 5 times, and the rest had used VR systems 6 to 15 times. When asked about prior incidences of cybersickness, 6 participants indicated that they had experienced some level of cybersickness previously. The perceived reasons for these experiences ranged from virtual movement when stationary, movement in a flight game, and technical issues like refresh rate, and jitter. No participants reported having the flu, taking any nausea-related medicine, or any other similar medical conditions. The experiment was approved by our university's research ethics board.

[7] With 6 students from laboratory (age from 20 to 34).

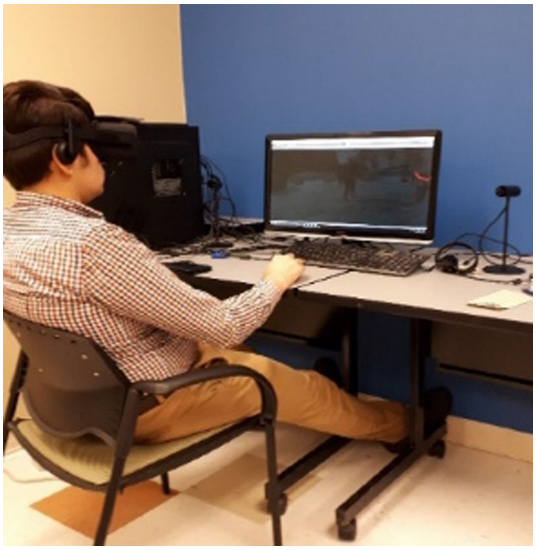

Fig. 7 Hardware setup, depicting a participant taking part in the experiment. Participants were seated on a fixed chair to avoid any movement or real body rotation

3.2.2 Apparatus

Hardware: The experiment was conducted using a PC (i5-6500 3.2 GHz CPU 3.2, GeForce GTX 970 GPU, 8 GB RAM) with an Oculus Rift CV1 head-mounted display. The input devices included an Eastern-Times Tech gaming mouse (ET7) and a keyboard. The setup is seen in Fig. 7. To avoid potential fatigue effects, or potential harm to participants (e.g., falling due to dizziness), participants were always seated. This also reduces any demand for postural controls (LaViola 2000).

Software: A custom virtual environment in Unity3D was developed (see Fig. 3) using an FPS demo level as a base. The game was customized to add data collection and to implement rotation snapping. NavmeshAgent were used for the enemies so that they would follow approach the player position, or main camera. NavmeshAgent is available via the Unity Engine AI system. As is typical of FPS games, the player view vector was coupled with mouse movement.

The player stood in the middle of the environment while a wave of 40 zombie enemies approached them. The participant avatar was depicted holding a gun, as the task involved shooting the zombies (Fig. 8) by centering a cursor on the zombies. This used ray-casting originating at the participant position to determine which zombie was hit. Each zombie wave took approximately 2 min to reach the player from their starting points. In total, there were 10 waves of 40 zombies each or 400 zombies in total. The starting positions of the zombies were consistent from one trial to the next. Since our study focused only on yaw rotation, camera roll and pitch were disabled. Thus, the zombies always appeared in positions where the participant could shoot them without the need to aim up or down. This was done intentionally to ensure participants did not use their head movement to aim as an excessive head movement could increase the cybersickness level (LaViola 2000). Character movement was disabled, and the participant was always positioned in the center of the environment to ensure that translation did not have any effects on the study. The experiment used two versions of the environment: one with rotation snapping, and one without. As described earlier, a black fading animation/transition was added during the snapping.

3.2.3 Procedure

Participants first signed a consent form, and the experimenter briefed participants on the experiment method and goals. Participants were informed that they could quit the study at any time, and for any reason, but especially if they

Fig. 8 Participant viewpoint during the experiment. Zombies are advancing on the participant position

felt too nauseous. The experimenter then explained the details of the task.

The task involved shooting at the zombies that appeared around the participant. To shoot a zombie, the participant had to use the mouse to center the viewpoint on the zombie and then press the left mouse button, much like most mouse-based first-person shooter games. If they successfully clicked/shot the zombie, the zombie would disappear. Zombies were positioned pseudo-randomly and distributed to appear outside of the field of view. This task was designed to necessitate a great deal of rotational viewpoint movement for participants to find and shoot them. Zombies would slowly advance from their starting position to the participant's position. If a zombie came within 3 meters of the participant's position without being shot, they still disappeared, but this was considered a miss/error for our performance-based dependent variable.

We used the same nausea survey (see Fig. 4) as in the preliminary experiment (Sect. 3.1), and similar to other studies on cybersickness (Davis et al. 2015). The survey appeared on the screen every 2 min, and the participant rated their current nausea level from 1 to 10 using the mouse. If they gave a score of 10, we advised them to withdraw from the experiment; three (3) participants withdrew in this fashion. Otherwise, participants performed the task in VR for a total of 20 min in either the RS or NS conditions.

Participants completed the SSQ questionnaire (Kennedy et al. 1993) twice: once before the experiment (Pre-SSQ) and once after. No participants reported a pre-SSQ score of greater than 7.48; this threshold is recommended as prescreening criteria to participate in cybersickness studies (Chen 2014). After completing the pre-SSQ survey, participants were also asked to sit and rest for 5 min before starting the experiment to ensure any effects from walking or running to the laboratory location would dissipate before commencing.

Following the completion of the experiment and the post-SSQ test, participants also completed the Witmer and Singer presence questionnaire (Witmer and Singer 1998). We then interviewed and debriefed participants. Participants were compensated with \$10 CAD for their time, which took roughly 45 min in total.

3.2.4 Design

Consistent with past cybersickness studies (So et al. 2001; Keshavarz and Hecht 2011), our experiment employed a between-subjects design, with a single independent variable: rotation snapping (enabled: *VS*, or disabled: *NS*).

The dependent variables included Total SSQ, Total Presence, and nausea scores (measured on a 10-point scale, as discussed earlier). We also recorded error rate as an objective performance metric. Error rate was the count of trials where a zombie came within 3 m of the participant. We hypothesized that when using rotation snapping, SSQ and nausea scores would decrease, but error rate and presence would be significantly worse due to the potentially jarring nature of the snapping.

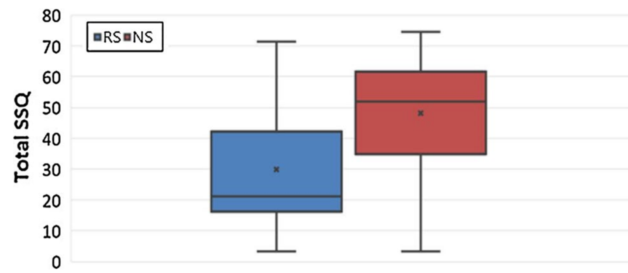

Fig. 9 Box plot of total SSQ Scores. Lower Score is better

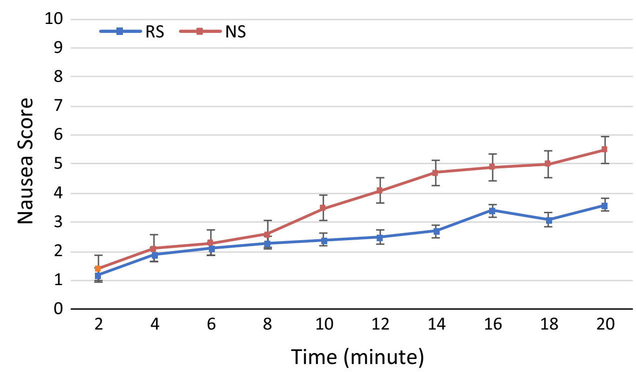

Fig. 10 Total nausea differences as a function of time. Error bars show standard error

3.2.5 Results

Total SSQ Cybersickness was quantified using the simulator sickness questionnaire (SSQ) (Kennedy et al. 1993), calculated as described in Sect. 2.1. Results for total SSQ scores are seen in Fig. 9. Overall, RS yielded lower SSQ scores compared to the NS condition with average scores of 29.8 and 48.1, respectively. We used an independent sample t test to compare the differences. There was a significant main effect for rotation snapping on total SSQ ($t\,(26)=2.3$, $p=0.026$, power = 0.79). Rotation snapping significantly lowered cybersickness levels compared to the control condition, as measured by total SSQ.

Nausea scores Nausea scores were taken every 2 min. Nausea scores as a function of time are seen in Fig. 10. As expected, nausea levels increased over time due to the excessive viewpoint rotation necessitated by the experimental task. What is interesting is that rotation snapping again reduced symptoms compared to the non-snapping condition.

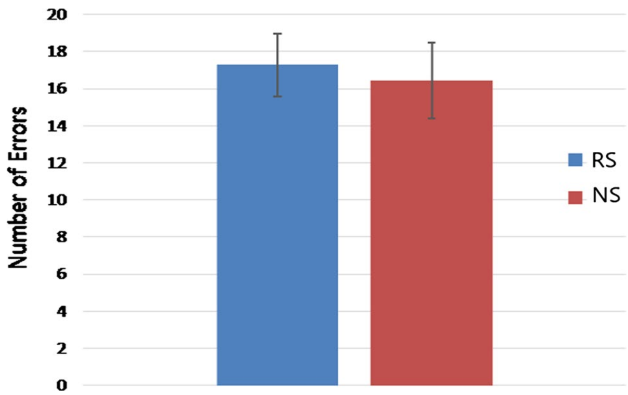

Fig. 11 Error rate by rotation snapping. Error bars show ± 1 SE

Repeated measures ANOVA revealed there was a significant main effect for rotation snapping on nausea scores ($F_{1,9}=20.7$, $p=0.0012$). The rotation snapping group had significantly lower nausea scores. The effect of time was also significant ($F_{9,9}=7.8$, $p=0.0027$). As seen in Fig. 10, nausea scores increased with time. However, the interaction effect between rotation snapping and exposure time was not significant ($F_{9,9}=0.9$, $p=0.5$), suggesting that both rotation snapping conditions increased in nausea at about the same rate. A longer experiment or a larger participant pool may reveal significant differences as the trends appear to start diverging at the 20-min mark and more strongly diverge by the 20-min mark in Fig. 10.

Error rate Error rate was a measure of user performance in the task, i.e., the total number of times a zombie reached the player. Error rate is summarized in Fig. 11. An independent sample *t* test revealed that the difference between the conditions was not significant (t (26) = 0.3227, $p=0.7$). While this does not categorically demonstrate that error rate is not affected by rotation snapping since one cannot "prove the null hypothesis" this way, we interpret this as a positive sign that any performance difference due to rotation snapping is potentially small.

Presence Similarly, the result of the 23-question Witmer and Singer presence questionnaire (Witmer and Singer 1998) revealed no significant difference between the RS and NS groups in terms of presence, as confirmed by an independent samples *t* test (t (26) = 1.9, $p=0.06$). Note that presence was slightly (but not significantly) lower for the RS group (mean = 4.16, SD = 1.2) than the NS group (mean = 4.89, SD = 1.4).

3.2.6 Discussion

Overall, rotation snapping significantly reduced participant cybersickness levels (per the SSQ) by about 40%. As argued earlier, this makes sense and is consistent with our expectations based on past research (Sharples et al. 2008; Chang et al. 2013a).

Of course, rotation snapping introduces a trade-off between user comfort and naturalism/realism, much like other cybersickness reduction methods, such as blurring, headlock, and field-of-view reduction ("tunneling"). Interviewing participants after the experiment revealed some additional insights. For example, 4 participants out of 14 in the RS condition mentioned that they initially found the snapping disoriented them. This may explain why this group had slightly, although not significantly, worse error and presence scores. However, after using it for a few minutes, participants indicated that they eventually got used to the snapping and it began to feel more comfortable. For example, one participant indicated that "at the start of the game it was annoying and frustrating to jump to different angles, but after 2 or 3 min" the participant "could control her actions better."

The result that presence and error rates were not significantly worse with rotation snapping was surprising and inconsistent with our hypothesis. This may suggest a limited impact of rotation snapping on objective user performance and presence in VR games. Further studies will help gather additional support for (or refute) this result, though this is not definitive at this time.

Interestingly, two participants did not even notice the snapping occurring during the experiment. We note that both participants had very limited VR experience—one had no prior exposure, and the other only had 1 to 5 prior VR experiences. After the experiment, when asked if they noticed the snapping, both indicated that thought that the snapping feature was part of the game. We also note that three participants mentioned that the transition animation was distracting. Two participants mentioned this was particularly true for large rotation angles, which made it more disorienting and harder to aim. That said, our objective error results suggest a limited impact on user performance. This may be due to task-specific factors, e.g., perhaps the task was too easy regardless of conditions.

Finally, as mentioned earlier, three participants withdrew from the experiment. We note that one of these withdrew from the RS condition at the 14-min mark. The other two withdrew from the NS condition, at the 4- and 7-min mark, respectively. It is noteworthy that these withdrawals occurred more frequently and much earlier without rotation snapping. This may indicate that rotation snapping can help increase VR exposure time before experiencing adverse cybersickness effects, but this too needs further exploration. Of course, our experiment task was an extreme example designed to elicit a cybersickness response.

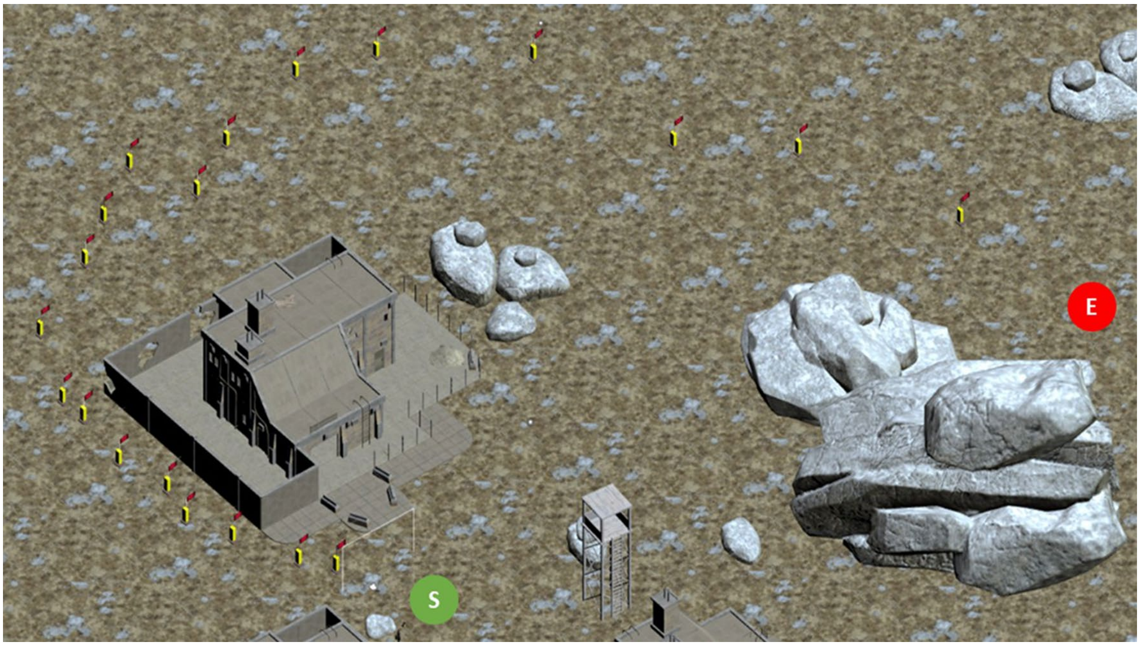

Fig. 12 Customized software environment for preliminary translation snapping study. The green circle is the starting point and the red circle is the endpoint. The small yellow markers are the flags (color figure online)

Overall, these results suggest promise for the idea of discrete motion. In the next section, we detail a second study adapting the principle of discrete motion to viewpoint translation, rather than rotation.

4 Experiment 2: translation snapping

We conducted a second study to evaluate the effectiveness of discrete motion when applied to viewpoint translation. As with the previous experiment, cybersickness was not our sole concern; after all, if the technique decreases cybersickness but yields a major user performance penalty, its benefits would be questionable. As a result, we measured its effects on performance and presence as well (Bowman et al. 1997). We recruited two groups of participants, who experienced both translation snapping and a control condition (i.e., no snapping) in two counterbalanced sessions.

4.1 Preliminary study

To design the discrete translation technique, we ran a preliminary experiment with 9 participants. In this experiment, we evaluated four different jump distances and gathered objective and subjective data. We collected and analyzed the optimal distance traveled, completion time, and participant preference. We used the results of this experiment to inform the design of our translation snapping technique, in particular, the delay between jumps when using continuous movement, and the most comfortable jump distance. This preliminary study employed normal viewpoint rotation (i.e., without any snapping); the task required relatively little viewpoint rotation and was intended to isolate viewpoint translation.

4.1.1 Participants

We recruited 9 participants (4 female, mean age of 27.8 years). Each participant was a student and the majority (6 participants) had experienced VR systems between 1 and 10 times. A single participant never used VR before, and 2 participants used VR frequently.

4.1.2 Apparatus

Hardware The experiment was conducted on an ASUS gaming laptop (i7-6700 HQ 2.6 GHz CPU, GeForce GTX 1070 GPU, 32 GB RAM) with an Oculus Rift CV1 head-mounted display. The virtual environment was created and rendered with Unity game engine. We used an Eastern Times Tech T7 gaming mouse as the input device.

Software The current study used the same FPS level demo as in the previous study (see Fig. 3) as a base, with experiment-specific customizations. We removed some 3D objects and scenes details to have wider space for navigation as well as to avoid user collisions with objects in the

Fig. 13 Participant viewpoint. Participants were instructed to approach each flag in sequence. Note: Only one flag is visible in the actual study

environment. We put 20 flags in the virtual environment denoting a path; participants were tasked with collecting these flags in order (see Fig. 12). The flags were initially invisible, and only one flag was active (visible) at a time. Viewpoint rotation behaved normally (i.e., there was no rotation snapping). Flags were positioned in a line (at different distances) positioned to require little rotation when traveling from flag to flag. This was intended to minimize rotation effects. Upon getting within 1 m of the active flag, it would disappear, and the next flag in the sequence would become active. In this fashion, the participant would follow the path seen in Fig. 12, one flag at a time. Upon reaching the active flag, a score counter incremented, and a chime informed the participant that they had reached their goal. The user's view is seen in Fig. 13.

Before the experiment, we calculated the optimal distance from start to endpoint of the total path (see Fig. 12) using the Unity AI (artificial intelligence) library. Specifically, we used a NavmeshAgent[8] employing the A* search algorithm to find the shortest path to the goal.

4.1.3 Procedure

After signing the consent form, we explained the test conditions to the participants. We asked them to use the mouse as an input device to collect active flags in the environment. We first showed them the control mapping using the mouse.

To simulate discrete jumps, participants were instructed to click the left mouse button to jump forward and right-click to jump backward. Upon pressing the button, the participant's viewpoint was instantly translated in the specified direction along the view vector. The software supported four different jump distances of 0.25 m, 0.5 m, 1 m, and 2 m. We selected these jump distances via pilot testing.[9] For example, in the 0.5 m condition, pressing the left mouse button would make the viewpoint snap forward by 0.5 m, while pressing the right mouse button would make it snap backward by 0.5 m. Viewpoint rotation was handled by mouse movement in a fashion consistent with first-person shooter games.

We encouraged participants to adjust their clicking speed to yield lower levels of discomfort; i.e., not too fast, and not too slow, at their discretion. They were instructed to collect all 20 flags, in sequence, for each of the four jump distance conditions. Before starting the experiment, participants put on the Oculus Rift HMD and practiced the study task for two minutes; these practice trials were not recorded.

After collecting 20 flags and finishing the first jump distance condition, we asked participants to close their eyes and rest for 30 s. After this break, we began the next condition. In total, the exposure time took approximately 10 to 12 min. Upon completion, we asked participants:

- Which speed did they prefer the most?
- Which one was the most comfortable?

Overall, the study took approximately 25 to 30 min. Participants were not compensated.

4.1.4 Design

The experiment employed a within-subjects design with a single independent variable, jump distance, with four levels (0.25 m, 0.5 m, 1 m, and 2 m). The numbers for jump distances were selected through pilot testing in the laboratory while developing the software. We counterbalanced jump distance ordering using a Latin square.

The dependent variables included *distance score* and *time score*. These scores represent the difference between the recorded time or distance traveled, and the optimal time or distance for a given condition (accounting for different jump distances). Since higher jump distances would allow

[8] https://docs.unity3d.com/ScriptReference/AI.NavMeshAgent.html.

[9] We tested several different distances with 6 members in the laboratory to select four different jump distances.

for faster travel (and hence shorter completion times), we normalized time as follows[10]:

$$\text{Time Score} = \text{completion time} - \text{minimum calculated time in each jump group}$$

where *completion time* is the actual time taken for participants to finish the entire travel task (i.e., collect all 20 flags in order). The *minimum calculated time* is the lowest time among participants for each jump distance group. Time score is measured in seconds, and lower time scores indicate better performance.

Also, as the optimal distance was constant (193 m) for the environment, the distance score was calculated as:

$$\text{Distance Score} = \text{traveled distance} - \text{optimal distance}$$

where *optimal distance* was always 193 m (as determined by the A* search algorithm—the most efficient path to complete the travel task) and *traveled distance* is the total distance each participant moved through the environment. The traveled distance was always equal to or greater than the optimal distance. Distance score is measured in meters, and a lower distance score indicates that the participant stayed close to the optimal path, and hence had less difficulty in controlling their movement.

4.1.5 Results and Discussion

One-way ANOVA revealed the effect of jump distance on distance score was statically significant ($F_{3,32} = 17.7$, $p < 0.05$). Post hoc comparisons using the Tukey HSD test indicated that the mean distance score for the 0.25 m jump distance ($\mu = 3.6$ m, SD = 0.8), 0.5 m jump distance ($\mu = 5.6$ m, SD = 0.9) and 1 m jump distances ($\mu = 9.5$ m, SD = 1.2) were all significantly better than the 2 m jump distance ($\mu = 23.7$ m, SD = 3.9), but not significantly different from each other. The 2 m jump distance seemed to have a dramatic effect on the overall deviation from the optimal path. Generally, smaller jump distances resulted in less deviation.

In addition, a one-way ANOVA was conducted to compare the effect of jump distance on *time score*. There was not a significant effect of jump distance on time score ($F_{3,32} = 2.5$, $p = 0.075$). The mean time scores were: 0.25 m ($\mu = 61.2$ s, SD = 11.1), 0.5 m ($\mu = 29.5$ s, SD = 9.8), 1 m ($\mu = 23.8$ s, SD = 6.3), and 2 m ($\mu = 37.5$ s, SD = 12.8).

Finally, we asked participants their preferences as to which jump distance was more comfortable and most preferred. Eight of the nine participants preferred a jump distance of 1 m, with the 0.25 m jump distance coming in second.

4.2 Formal study 2: evaluation of translation snapping

Based on the results of the preceding experiment, we decided to use a jump distance of 1 m for our translation snapping technique. We note that 1 m should not be taken as a universally best jump distance since this also depends on the study task and environment. For example, in a medical training simulation, 1 m might be too long. Similar to rotation snapping distance, this is another parameter that is likely best calibrated on a per-user or per-task basis.

Before implementation, we wanted to ensure that for the formal study, both test conditions used the same input method, which involved holding the mouse button to move forward. Hence, rather than pushing a button repeatedly, participants could instead simply hold the button. This approach makes translation snapping more comfortable and less fatiguing on the finger. We added a time-out delay between jumps based on how quickly the participants clicked the mouse in the preliminary experiment. This ensures that the translation snapping did not operate continuously (which would be effectively indistinguishable from teleportation), but rather, would happen at regular intervals while the mouse button was held down.

As indicated earlier, we instructed participants in the preliminary study to click the mouse at a comfortable speed (i.e., not too fast or too slow). We used this clicking speed to determine the average number of clicks per second, which in turn yields the average number of jumps[11] performed each second. On average, with the 1 m jump distance, participants clicked 2.4 times per second. Phrased differently, they jumped roughly every 416 ms on average. We incorporated this delay into our translation snapping technique; holding down the mouse button issued a jump event every 416 ms. This ensures we have a discrete movement with analog input.

Unlike the rotation snapping technique, we did not apply a fading animation during translation snapping. Jumping with a 416 ms delay was quite fast. A fading animation would result in the screen constantly blinking, which we felt may be distracting or even cause eye strain.

[10] We also normalized the scores with standard score formula: Time score $= \frac{\text{calculated time} - u}{\sigma}$; where μ is the mean and σ is the standard deviation of each jump distance group. The result was the same for both formulas. By doing this, we ensure that scores are normalized based on jump distance average score, since otherwise, the 2 m jump distance would always have the best score.

[11] One jump occurs with each click; hence, the number of clicks can be calculated from the traveled distance. For example, traveling 193 m with the 1 m jump distance required 193 clicks.

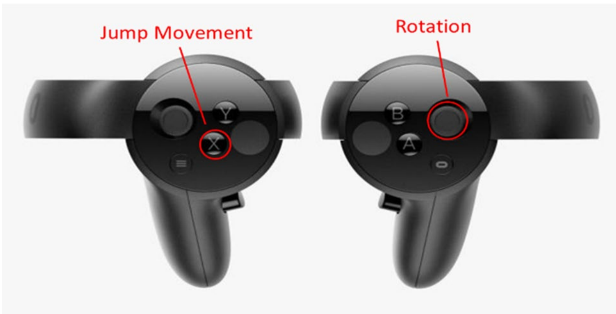

Fig. 14 Oculus touch controller and its controller mapping

Fig. 15 Hardware setup, depicting a participant taking part in the experiment. The chair position was fixed to avoid real body rotation

4.2.1 Participants

We recruited 20 participants aged between 18 and 39 years (mean age of 28.7 years, 14 male, 6 female). Participants had a wide range of experience with HMD VR systems: 3 participants had never used a VR system before, while 2 participants used VR frequently (1 to 6 times per week). Of the remaining participants, 9 had used VR between 1 to 5 times, and the rest had used VR systems 6 to 15 times.

When asked about prior incidences of cybersickness, 7 participants indicated that they had experienced some level of cybersickness previously. None of the participants reported having the flu, taking any nausea-related medicine, or any other similar medical conditions. Ten participants did not consider themselves susceptible to motion sickness (Golding 1998), but seven participants reported that they were slightly susceptible to motion sickness. Two participants considered themselves moderately susceptible and one participant believed that he was very prone to cybersickness. With the exception of four participants who wore glasses, all participants had normal vision. Participants who wore glasses keep their glasses on. The study run in 2 sessions,

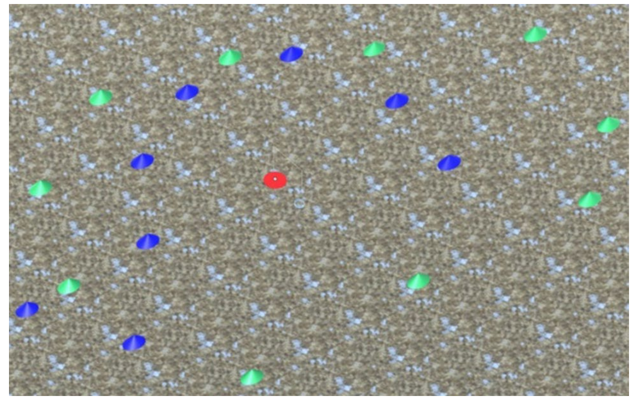

Fig. 16 Overhead view of virtual environment and waypoints—the green cones served as single waypoints and the blue cones served as double waypoints (i.e., the participant must travel to 2 blue cones in these trials) (color figure online)

separated by a 10 to 48-h gap. Participants were compensated $10 CAD upon completion of the second session.

4.2.2 Apparatus

Hardware The experiment was conducted on an ASUS (Model: GL502VS) gaming laptop (i7-6700 HQ 2.6 GHz CPU 2.59 GHz, GeForce GTX 1070 GPU, 32 GB RAM) with an Oculus Rift CV1 head-mounted display with 2 tracking cameras. We used the Oculus touch controllers as input devices (see Fig. 14).

To move forward, participants pressed and held the x button. Holding the button caused the viewpoint to jump forward in 1 m increments, every 416 ms as described above (Sect. 4.2). Viewpoint rotation (which also controlled movement direction) was controlled using the right thumbstick, consistent with many first-person video games. The setup is seen in Fig. 15. To avoid potential fatigue and also reducing any demand for postural controls, the participants were seated (LaViola 2000).

Software We designed a virtual environment for our study using the Unity 3D game engine (version: 2017.1.1f1). To avoid participant distractions, we removed all objects and landmarks from the environment terrain. The ground was flat and used a desertlike texture that uniformly repeated over the ground. The software displayed 10 bright green cones and 8 blue cones that served as waypoints, and a red circle showing the starting position. The environment is depicted in Fig. 16.

The task involved navigating from the starting position (red circle) to the green and blue cones and was modeled after a path integration task used in previous work (Loomis et al. 1993). This kind of task gives an indication of the user's spatial awareness, reflected in their ability to determine their original starting point upon reaching a specific

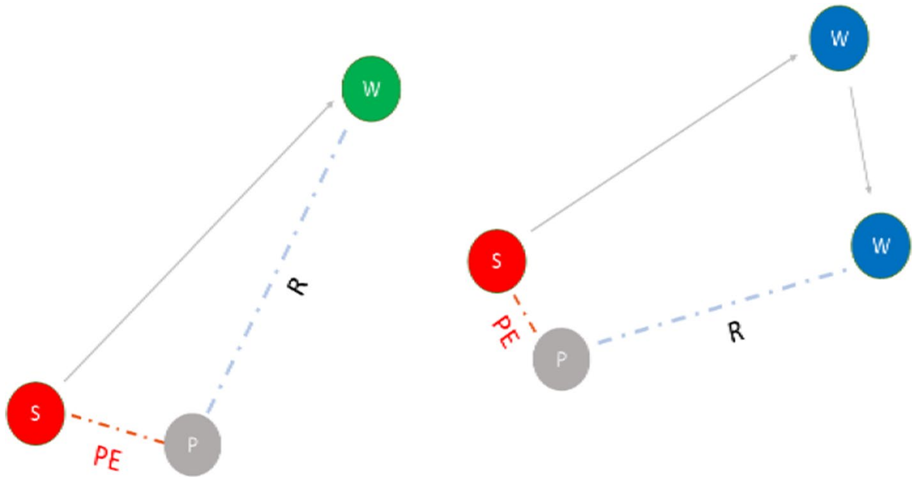

Fig. 17 Single and double waypoint tasks, and calculation of pointing error. (Left) Single waypoint trial: The participant starts at the red circle (start position) and moves to the green circle. R is the ray and P is the point selected by participants. The distance between P and the start position is PE (pointing error). (Right) Double waypoint trial: The participant starts at the red circle and moves to the first blue waypoint, then the second one, in sequence. Participants performed the point selection task after reaching the second waypoint. PE is calculated in the same fashion as single waypoint trials (color figure online)

waypoint. We used this task to determine if translation snapping negatively impacted participant spatial awareness.

At the start of each navigation trial, participants were positioned on the red circle (start location). A single cone would be active and visible—all other cones were initially deactivated (invisible). Participants were instructed to move to the active cone by rotating their viewpoint to control their movement direction, then holding the "X" button as described above to move forward (regardless if they were in the TS (Translation Snapping) or NTS (No Translation Snapping) condition). There were two kinds of trials: single waypoint "green cone" trials, and double waypoint "blue cone" trials. For green cone trials, the participant had to simply travel to the position of the cone. For blue cone trials, the participant had to travel to two cones, first the visible one, then a second one that appeared upon reaching the first. Upon reaching a green cone or second blue cone, both the cone and the starting red circle would disappear. This was intended to further assess the possible loss of spatial awareness due to translation snapping. Both types of trials are depicted in Fig. 17.

In total, up to 18 waypoint cones—10 green and 8 blue—located around the start position at different distances would appear. Participants first finished two single waypoints (green) trials (S), followed by one double waypoint (blue) trial (D). They repeated this ordering for 10 single waypoint trials, and 4 double waypoints trials per session (SSD, SSD, SSD, SSD, SS), for 14 trials total. This task order prevented participants from memorizing the path by repeating single waypoint trials repeatedly; double waypoints would increase the need for spatial awareness in the next part of the task, which involved pointing back at the starting location.

Upon reaching the waypoint, participants were instructed to point the Oculus Touch controller ray back to where they thought the original start position was. Visually, this appeared as a blue ray emitted from the right Oculus Touch controller, and a cursor drawn where the ray intersected the ground (see Fig. 18). Upon pressing the trigger button, the *pointing error* dependent variable was calculated, and the participant was positioned back at the start location for the next trial.

The purpose of using this "teleportation" sub-task was to provide a measure of how well participants could perform path integration during translation snapping. It allowed us to quantify how the TS or NTS conditions

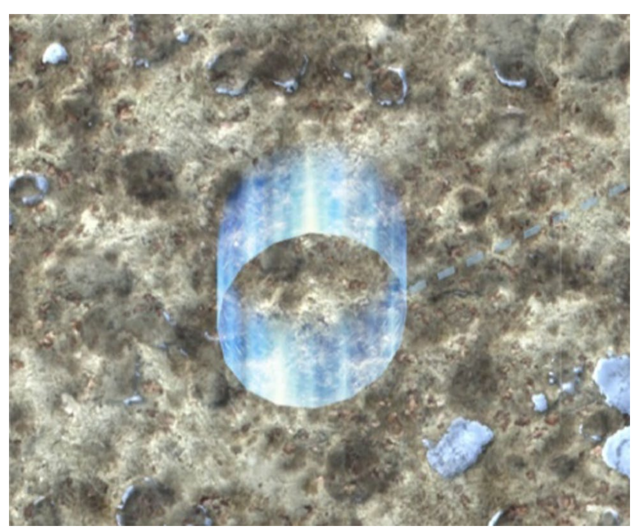

Fig. 18 Cursor as an indicator for users' teleport point

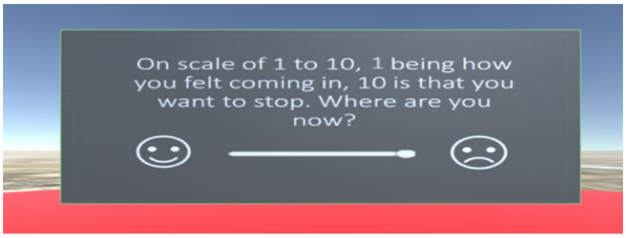

Fig. 19 Nausea (discomfort) scale on-screen questionnaire. Emojis were removed from this study to ensure participants' nausea ratings were only based on numbers

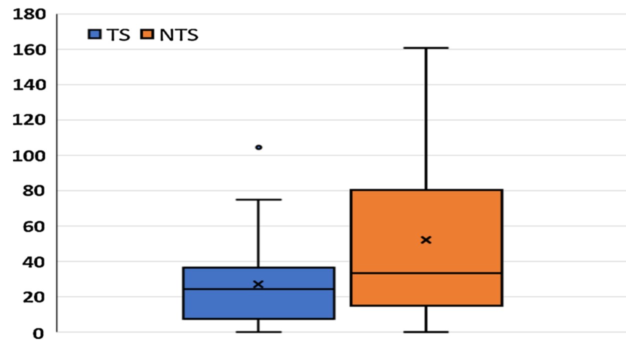

Fig. 20 Box plot of total SSQ Scores. Lower Score is better

affected user ability to correctly rotate to the start location, and how close to the start they could get. After all, poor path integration is a possible negative side effect of translation snapping. We called this metric *pointing error* (PE for short). PE was calculated as the distance between the user selected point to the actual original starting point. The task (both for single waypoint green cones and double waypoint blue cones), as well as a depiction of PE, are seen in Fig. 17. We chose this task because cybersickness primarily arises due to movement in the environment, and for translation snapping to operate, the user must be moving, hence the task must elicit motion.

4.2.3 Procedure

Participants first signed an informed consent form. The experimenter then explained the task. Participants were informed that they could quit the study at any time, and for any reason, but especially if they felt too nauseous. The experimenter then explained the details of the task. Participants were divided into two gender and age-balanced groups. The first group experienced the translation snapping (TS) condition in the first session and the no-translation snapping (NTS) condition in the second session. The second group experienced the conditions in the opposite order. The experiment was approved by our university's research ethics board.

First, we asked participants to fill demographic forms and pre-SSQ questionnaire to ensure they did not present any cybersickness symptoms before beginning the study. If their Total Sickness was greater than 7.48 (Chen 2014), we asked them to rest for 5 min or postpone the study. All participants scored lower than this. Afterward, we explained the task, the controls and then we asked them to practice the waypoint travel task for 2 min. Practice trials were not recorded. Participants only completed the practice trials on their first session, since by the second session, they were already familiar with the apparatus and task.

Participants performed the waypoint travel task as described above in Sect. 4.2.2 with both the TS and NTS conditions, one condition per session. Condition order was counterbalanced with half of the participants completing TS in the first session, followed by NTS in the second session, and the other half in the opposite ordering.

Every minute, a nausea questionnaire (Fig. 19) appeared on the screen, and the participant rated their current nausea level from 1 to 10, similar to previous studies (Davis et al. 2015). If they gave a score of 10, we advised them to withdraw from the experiment; two (2) participants withdrew in this fashion. Otherwise, participants performed the task in VR on average around 12 min in total, in either the TS or NTS conditions (24 min of exposure in total).

Following the completion of the experiment and the post-SSQ test, participants also completed the Witmer and Singer presence questionnaire (Witmer and Singer 1998). We then interviewed and debriefed participants.

4.2.4 Design

Our experiment employed a within-subjects design with a single independent variable: translation snapping (enabled: *TS* or disabled: *NTS*).

The dependent variables included Total SSQ, Total Presence, pointing error (PE, calculated as described above), and nausea scores (measured on a 10-point scale, as discussed earlier).

4.2.5 Results

Two participants withdrew from the study in NTS condition. We removed their results. We kept their results for post-SSQ scores and used their last nausea score before their withdrawal (So et al. 2001).

Total SSQ Results for total SSQ scores are seen in Fig. 20. Overall, TS yielded lower SSQ scores compared to NTS, with average scores of 27.1 and 52.1, respectively. A within-subject sample t test was conducted to compare the differences in total SSQ between the TS and NTS conditions. There was a significant main effect for translation snapping on total SSQ (t $(38)=2.09$, $p=0.021$, $power=0.81$). Total

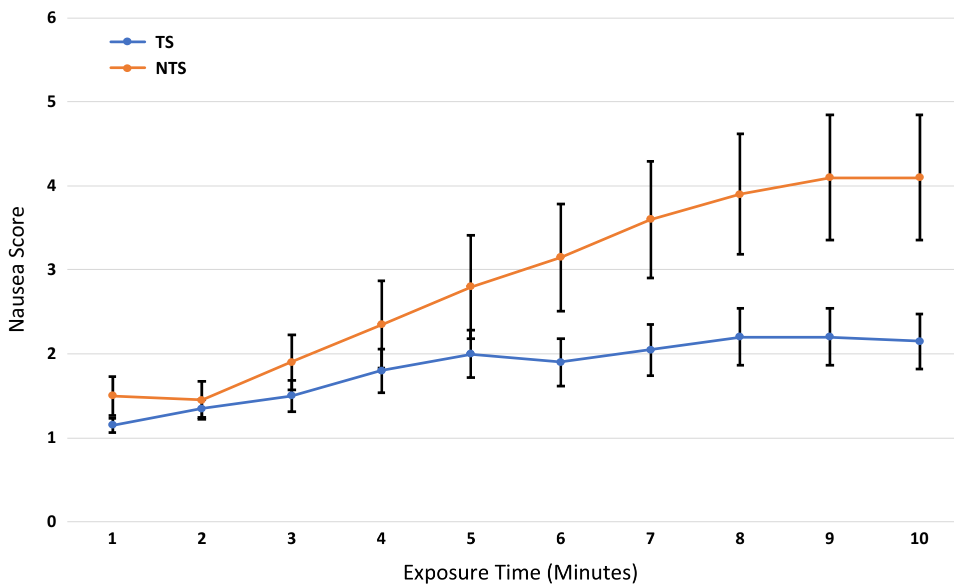

Fig. 21 Average nausea scores as a function of exposure time. Error bars show standard error

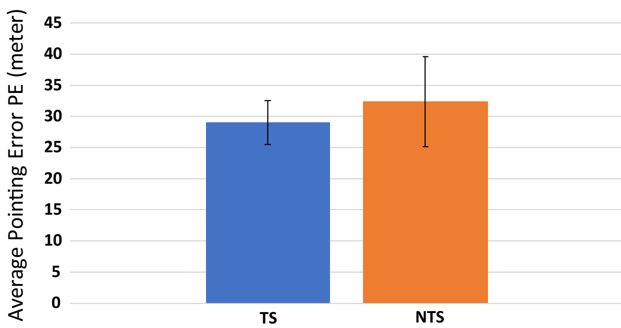

Fig. 22 Average pointing error (PE) by translation snapping. Error bars show ± 1 SE

SSQ scores were significantly lower in the TS condition than the NTS condition.

Nausea scores Nausea scores were taken once per minute. Nausea scores over time are seen in Fig. 21. Overall, TS yielded lower nausea scores than NTS. We performed repeated-measures ANOVA treating translation snapping and exposure time as factors. There was a significant main effect for translation snapping on nausea scores ($F_{1,19} = 5.48$, $p = 0.03$). TS offered significantly lower nausea scores. Unsurprisingly, nausea levels increased over time due to exposure to increasing cybersickness effects (Kennedy et al. 2000). This effect was also significant ($F_{9,171} = 13.96$, $p < 0.0001$). As seen in Fig. 21, nausea scores generally increased over time with both the NTS and TS conditions. However, there was a significant interaction effect between translation snapping and exposure time ($F_{9,171} = 5.04$, $p < 0.0001$). As seen in Fig. 21, nausea scores increased at different rates, diverging significantly after about 6 min of exposure.

Average pointing error Average pointing error (PE) was calculated as described in Sect. 4.2.2. Average PE scores are seen in Fig. 22. An independent sample t test was conducted to compare differences in pointing error between TS and NTS. The difference was not significant (t (34) = 0.4, $p = 0.6$, $n = 18$). Although both conditions reveal relatively poor performance for average pointing error (at around 32 m from the original starting point), TS was not significantly worse than NTS, suggesting that the technique may not affect path integration that much.

Presence score We used a customized 16-question version of the Witmer and Singer (Witmer and Singer 1998) presence questionnaire, selecting the subset of questions mostly related to our study. The average presence score for TS (μ = 4.2, SD = 2.1) was not significantly different than NTS ($\mu = 4.1$, SD = 2.2, $n = 18$), as confirmed by an independent samples t test (t (34) = 0.17, $p = 0.8$).

4.2.6 Discussion

Overall, much like rotation snapping, and consistent with our expectations based on previous work (Sharples et al. 2008; Chang et al. 2013a), translation snapping significantly reduced participant cybersickness levels (per the SSQ) by 47%. Like rotation snapping, translation snapping also appeared to have minimal impact on presence scores. Participants also did not report breaks in presence due to snapping. Unlike the rotation snapping study, none of the participants reported any disorientation due to the jumping movements. There are two possible explanations for this. First, we did not employ a fading animation with translation snapping, unlike rotation snapping. It is possible this fading effect was partially responsible for disorientation with rotation snapping. A second possible reason is that we took greater care to "calibrate" the translation snapping jumping distance based on user preference, unlike rotation snapping, which was instead optimized to reduce nausea.

Six participants reported they felt noticeably more nausea when rotating the viewpoint than with translational movement. These comments were unsurprising; after all, we did not use any rotation-based technique like rotation snapping (Farmani and Teather 2018) or tunneling (Fernandes and Feiner 2016). We note that since both the TS and NTS conditions used the same mechanism for rotation, this rotation effect was equal in both conditions.

A few participants suggested changing controller mapping for the teleportation sub-task. For example, they suggested using the trigger button on the same controller for teleportation. Two participants also suggested they would prefer to use the thumbstick for movement, rather than using the x button. While we will consider these suggestions for future studies, we do not expect that this influenced our results.

5 Conclusions

In this article, we established operational parameters for, and then evaluated two techniques for reducing cybersickness caused by visual-vestibular conflicts in stationary VR setups. Our techniques—rotation and translation snapping—were motivated by previous research on discrete movement and inconsistent locomotion to reduce vection or illusionary of self-motion in virtual reality environments.

The first technique was designed to employ discrete rotational movement and called rotation snapping (RS). The rotation snapping technique was designed based on a preliminary experiment, assessing discomfort levels of 12 participants at 11 different rotational speeds. The result of this study provided a threshold for activating rotation snapping, to reduce cybersickness when the participants reported the highest level of discomfort. Our technique also included a black fading transition between viewpoints to hide the discrete movements. For evaluating rotation snapping, we ran a user study with 28 participants in two different groups (14 participants in each group) in the FPS game scenario. We compared rotation snapping to a control condition (without rotation snapping) and measured Total SSQ score, nausea score, presence, and error rates (miss trials). Our results suggest that rotation snapping did indeed decrease SSQ-reported cybersickness by as much as 40% and also slightly reduced nausea score, especially over longer exposure times. Also, presence and error rate were not significantly affected by VS technique.

The second technique, translation snapping (TS) was based on reducing vection during translational movements by using "jumping" movement. Like with rotation snapping, we ran a preliminary experiment to evaluate four different jumps distances. The outcome of this study gave us a threshold for the most comfortable jump distance, as well as an appropriate speed with which to activate it (e.g., during continuous button/joystick pressing). To evaluate translation snapping, we ran a user study with 20 participants in two different sessions on different days, comparing TS to a control condition (without snapping). We compared total SSQ score, nausea scores, and presence. The task required path integration, to help determine if discrete motion negatively affected participant spatial awareness (and hence wayfinding ability). Much like the results of the rotation snapping experiment, the results of this study suggest that translation snapping is also effective at decreasing cybersickness. SSQ scores decreased by 47% when employing translation snapping. Translation snapping also significantly reduced nausea scores, especially with longer exposure time. Moreover, the results of the study showed that presence levels and performance (pointing error) were not significantly affected by the TS technique. Participants were equally (roughly) able to point back to their initial starting position with both TS and NTS. This suggests that TS may not substantially impact path integration. While this is further supported by participant comments around their apparent lack of disorientation (as compared to rotation snapping), further study is needed.

In conclusion, both techniques achieved our objective of reducing cybersickness, and nausea. Our results globally suggest both techniques also have a potentially low cost in terms of user performance and presence. Overall, our results are promising and motivate us to further study and the effects of combined rotation and translation snapping in VR environments.

5.1 Limitations and future work

As discussed earlier in Sect. 3.1.5, there is a potential confound in our rotation snapping preliminary experiment, from which we derived our rotational speed threshold at which to activate rotation snapping. For our purpose, the 25°/s threshold appeared to be effective, despite the potential confound—our rotation snapping condition did indeed reduce cybersickness. Nevertheless, future work will focus on establishing more reliable thresholds, since it is possible our current implementation unnecessarily activates rotation snapping at lower rotational speeds than is strictly necessary. A more well-established snapping threshold may yield better results. We thus propose to redesign both translation and rotation snapping techniques to consider the speed of camera movement or rotation. In the current study, we only used thresholds which may not work in all scenarios.

Another limitation of the rotation snapping evaluation is the fact that participants were stationary while performing the zombie shooting task. Testing the effectiveness of rotation snapping during free-roaming navigation is a clear opportunity for future studies and would allow us to evaluate the effectiveness of rotation snapping in more realistic tasks. Other topics for future work include determining an empirically validated snapping range. We used 22.5° in the current experiment based on informal pilot testing. Likely, "fine-tuning" this parameter by testing different snapping ranges (potentially dependent on rotational speed) will yield better results. Also, the choice of task in cybersickness experiments is critical to determine the impact of cybersickness reduction techniques on user performance. For instance, the task used in the RS formal study may have been too easy for participants in *both* conditions, and thus did not elicit a sufficient difference in performance. So, further research could help better establish the relationship between task difficulty, cybersickness reduction technique parameters, and their interrelated effect on user performance.

In the translation snapping study, when participants withdrew, we used their last score (which was near to 10) as their score for remaining minutes. In cybersickness studies, exposure time can be more important than the task. Feiner and Fernandes (2016) proposed a raw discomfort score, that allows one to calculate nausea score with respect to time. This normalizes the score and gives an indication of when a participant should withdraw (before becoming too sick). While we did not use these discomfort scores in the current work, we plan to employ them in future studies.

Finally, a clear topic for future work is to include both rotation snapping *and* translation snapping together. For example, translation snapping could be employed during linear movements, comparing trials both with and without rotation snapping. Such an experiment would determine which technique is more effective in reducing cybersickness, or if they work best together, and in a more naturalistic VR navigation task.

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