To cite this version :

Mohammad Ali MIRZAEI, Frédéric MERIENNE, Jean-Rémy CHARDONNET - Influence of navigation parameters on cybersickness in virtual reality - Virtual Reality - Vol. 25, n°3, p.565-574 - 2020

Influence of navigation parameters on cybersickness in virtual reality

Jean-Rémy Chardonnet*[1], Mohammad Ali Mirzaei[2], Frédéric Merienne[1]

[1]LISPEN EA 7515, Arts et Métiers, Univ. Bourgogne Franche-Comté, HeSam, Institut Image, 2 rue Thomas Dumorey, 71100 Chalon-sur-Saône, France

[2]Instrument Technology, Atlas project, Embedded and FPGA team, Highview House, Station Road, Edgware and U.K.

Running head: Influence of navigation parameters on cybersickness in virtual reality

*Corresponding author:

Institut Image, 2 rue Thomas Dumorey, 71100 Chalon-sur-Saône, France.

Tel. +33.3.85.90.98.73

jean-remy.chardonnet@ensam.eu

Abstract

Cybersickness remains a major challenge in the virtual reality community. It occurs mainly when navigating in a 3D immersive virtual environment. Several parameters are known to influence the users' cybersickness level while navigating, that can be either technological or neuro-psychological. This study investigates two of these parameters that are the distance from a virtual barrier and the choice of the navigation interface.

An experiment was performed for each of these parameters to evaluate their influence on the variation of cybersickness. For each experiment, participants were asked to navigate in a large virtual room with walls that were textured with a black and white lined pattern to voluntarily exacerbate cybersickness. The level of cybersickness was collected through subjective (Simulator Sickness Questionnaire) and behavioral (evolution of postural sway) measurements. Results allow drawing suggestions for optimal navigation, so that cybersickness can be significantly reduced, thus providing with enhanced user experience.

Keywords

Cybersickness, navigation, parameters, navigation device, virtual reality

1. Introduction

With the rapid development of virtual reality (VR) and the introduction on the market of low-cost head-mounted displays and interaction devices, major challenges still need to be addressed so that VR technologies can be massively spread in various application fields. Among these, cybersickness represents a highly critical issue and is still receiving much attention. A strong parallel was done for years with research on motion sickness and visually-induced motion sickness (VIMS) (e.g., Bos et al., 2008; Oman, 1990), as symptoms of cybersickness can be very similar: cold sweat, belching, retching, pallor, headache, nausea, possible vomiting.

In the virtual reality field, three main theories try to explain the origins of cybersickness. The first theory is the well-known sensory conflict, stating that "*motion sickness is a self-inflicted maladaptation phenomenon which occurs at the onset and cessation of conditions of sensory rearrangement when the pattern of inputs from the vestibular system, other proprioceptors and vision is at variance with the stored patterns derived from recent transactions with the spatial environment*" ((Reason & Brand, 1975), pp. 274–275). This theory is well accepted in the VR community, e.g., (Kolasinski, 1995; Akiduki et al., 2003; Kemeny, 2014). The second theory compares sickness to food poisoning, stipulating that undesirable stimulations found in some virtual environments (VE) can affect the visuo-vestibular system in such a way that the body considers that it has ingested toxic substances (Treisman, 1977). This theory is less admitted in the VR community since it lacks prediction power and does not explain why some cybersick users do not have emetic reactions. The third and last theory is postural stability, stating that subjects who cannot maintain their balance may experience sickness (Riccio & Stroffegen, 1991). In recent years, this theory has been the center of attention and is taken into consideration in the VR community, e.g., (Cobb, 1999; Kennedy & Stanney, 1996; Murata, 2004; Chardonnet et al., 2017).

Different parameters are involved in the occurrence of cybersickness that can be either technological or neuro-psychological. Latency (Wilson, 2016), the field of view (Lin et al., 2002; Sharples et al., 2008), low frame rates (LaViola, 2000), an inappropriate adjustment of navigation parameters (So et al., 2001), navigation interfaces (Mestre, 2014) or an incorrect selection of scene contents (Lo and So, 2001) are factors that are often investigated. For example, latency jitter introduced in a head-mounted display was shown to significantly increase self-reported cybersickness (Stauffert et al., 2018). Predictive compensation for head movements can be a solution to lower latency and thus to reduce cybersickness (Buker et al., 2012). Cybersickness can also be related to circular and linear vection, image velocities or pseudo Coriolis and Purkinje effects. Past research showed that vection may be a prerequisite for VIMS (Keshavarz et al., 2015), but the relation between vection and cybersickness appears to be in fact much more complex (Palmisano et al., 2017), though vection change was shown to significantly increase cybersickness (Bonato et al., 2008).

In this paper, we focus on the effects of navigation parameters, namely the distance to a virtual barrier and the navigation interface, on the level of cybersickness. Past research also studied the effect of navigation speeds and provided some recommendations in terms of optimal thresholds for translational and rotational speeds in a VE to limit cybersickness (Kemeny et al., 2015; So et al., 2001). Notably, So et al. (2001) showed that depending on the navigation speeds, onset times of cybersickness can be significantly affected, but not the ratio between the increase of sickness and the duration of exposure. Much effort has been put in evaluating the effect of rotational speeds, as it is known to strongly encourage the occurrence of sickness (see for example (Hu et al., 1988; Farmani & Teather, 2018)). Here we chose to concentrate on translational movements to keep it simple. Other work considered rather acceleration than speed as being highly influent on cybersickness (Lloarch et al., 2014; LaValle, 2017, Hsiao et al., 2018). Especially, LaValle (2017) stated than acceleration was even a bigger contributor to cybersickness than other factors because of a strong induced vection. Therefore, controlling accelerations should be more efficient to reduce cybersickness, as proposed for example by Plouzeau et al. (2018), rather than controlling speeds, as for example in (Argelaguet, 2014). Regarding navigation interfaces, past work reported a major effect on cybersickness. For example, Chen et al. (2013) compared a classical joystick-based interface and steering-based navigation, and found significantly lower cybersickness levels with a steering-based paradigm than with joystick-based interaction. The result was explained by (i) a big difference in visuo-vestibular stimulation (joystick-based interaction does not encourage stimulating the inner ear, to the contrary of steering-based paradigms), and (ii) a better control of movements when using the steering-based method than with a joystick-based interface (navigation tends to not be smooth with joystick-based interfaces). Coomer et al. (2018) compared four navigation techniques – joystick, teleportation, point-tugging and arm-cycling – and obtained significant differences among them in terms of cybersickness levels with joystick-based methods being much more prone to cybersickness than teleportation and arm-cycling. Natural gesture-based techniques are another well-considered solution for an improved VR experience. Among them, walking-in-place (WIP) was much studied over the past years (Slater et al., 1995), as it allows an enhanced sensation of walking with higher presence than joystick-based techniques (Razzaque et al., 2002). However, some work revealed WIP to generate more cybersickness (Usoh et al., 1999).

We contribute to this research by exploring the influence of the distance from a virtual object and the navigation interface itself. We have not considered other parameters, as we wanted to stick to navigation implementation matters rather than neuro-psychological considerations. However, it is clear that cross effects of parameters influencing cybersickness exist. In this study, the level of cybersickness was estimated based on the features proposed in Chardonnet et al. (2017). In their study, the shape, the area and the difference between low frequency and high frequency components of the user’s postural sway were introduced as a set of efficient features to estimate and predict cybersickness during navigation in a virtual environment. Results suggested that when cybersickness occurs, the projection of the user’s center of gravity, as measured by a balance board, describes a shape that evolves from an ellipse to a circle and grows in size. Moreover, the analysis of the postural sway signals in the frequency domain reveals an emergence of high frequency components in the presence of cybersickness (low frequency components represent voluntary movements while high frequency components indicate involuntary movements; the limit between low and high frequency components is set to 1Hz). The difference between low and high frequency components tends to increase as cybersickness intensifies. Furthermore, this difference was shown to strongly correlate to cybersickness scores as measured by the well-known Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993).

Compared to recent work focusing on using head-mounted displays exclusively, we chose to use a CAVE system that (i) allows not being totally shielded from reality and (ii) allows a wider field of view, these factors being considered as contributing to the occurrence of cybersickness (Lin et al., 2002; Sharples et al., 2008). Note that here we do not aim at proposing methods to reduce cybersickness, as it is beyond the scope of this paper. Nonetheless, we will provide some suggestions for future research.

Throughout this paper and for each experiment, postural sway as considered in Chardonnet et al.’s work (Chardonnet et al., 2017) and cybersickness scores as measured by the SSQ will be considered as metrics for evaluating the influence of the above-mentioned navigation parameters on cybersickness:

- Postural sway signals will be analyzed in the frequency domain after performing a Fast Fourier Transform in order to get the corresponding spectra. The differences between low and high frequency components will be computed. The spectra are limited to 0-20Hz (TechnoConcept, 2007). In fact, since body movements are not extremely fast due to the body's natural inertia, high frequencies cannot extend to higher than a specific limit to avoid strong noise. On the other hand, movements can contain 0Hz components, which means that the body is in a standing posture without any voluntary and involuntary movements.

- Cybersickness scores will be calculated in a slightly different way than the one provided by the SSQ scoring guideline: each rated score of each symptom for each symptom cluster (nausea, oculomotor, disorientation) will be added, each cluster score will be then multiplied by their specific weight factor, all the three subscores will be finally summed up weighted by 3.74. This will lead to possibly higher values than 300 (this value being defined by Kennedy et al. (2003) as the maximal value for SSQ scores).

The paper is organized as follows. We first present in Section 2 the VR setup and the navigation interfaces we chose to use and compare. Then in Section 3 and Section 4 two experiments are described corresponding to the study of the distance from a virtual barrier and the navigation interface, respectively. We conclude in Section 5, giving some perspectives.

2. Navigation interfaces

Here we present two navigation interfaces that were used in the different experiments, that correspond to two main families of interfaces: a device-based navigation interface (DBNI) and a natural gesture-based navigation interface (NGBNI).

2.1 Virtual reality setup

Before describing the different navigation interfaces, the virtual reality setup that was used throughout the experiments, is presented. It consists of a 3x3x3m four-sided CAVE system with a 1400x1050px resolution per side. Stereoscopic image is projected through two Projection Design F30SX+ per side. An ART infra-red-based optical tracking system is used to track users in position and rotation, as well as interaction devices.

A homemade software development platform was developed in C++ to manage the connections within the whole VR equipment. Application development was achieved through JavaScript. OpenSceneGraph was used to render 3D virtual environments, on top of OpenGL. MPI and four NVidia Quadroplex GPUs allow projecting the generated model at 60fps. Devices are connected through Virtual Reality Peripheral Network (VRPN). The overall latency is estimated at around 40ms.

2.2 Device-Based Navigation Interface (DBNI)

The first navigation interface is based on a Flystick, a wand-like device with an embedded joystick. Joystick-based devices are widely used for navigation purposes (Bowman et al., 2004) and are well-known among gamers, which justifies our choice for considering them in this study. Users are capable of moving forward/backward and turn to the left/right up to ±15°, if required. The Flystick has five buttons, one joystick handle, an infra-red-based optic tracker (position and orientation) and a trigger button. Figure 1 demonstrates the upper view of a Flystick with a label on each button. The joystick handle sends forward/backward commands to the navigation system. Rotations are by default commanded by turning the handle to the left and right (first option). However, the navigation system can also perform rotational movements by reading the instantaneous orientation of the optical trackers attached to the Flystick and redirecting user movements along the Flystick orientation (second option). The navigation task is initiated and terminated when users push the buttons labeled “Start” and “Stop”, respectively. The additional “+” and “-” buttons were not used in this study.

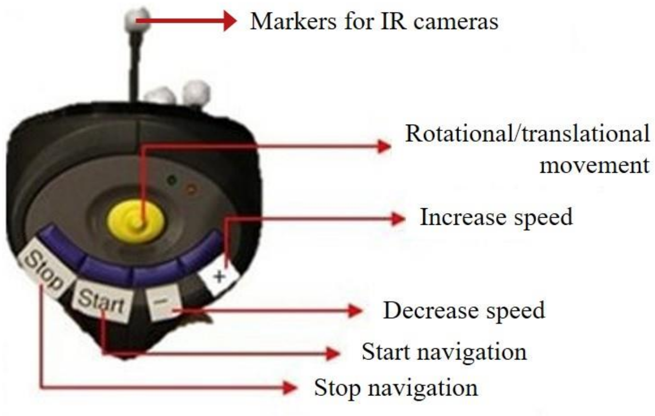

Fig. 1 Flystick and navigation functions assigned to each button.

2.3 Natural Gesture-Based Navigation Interface (NGBNI)

The second interface is based on natural body movements, which allows for increased naturalness of navigation in virtual environments (Usoh et al., 1999). Body movements include walking, hand and head movements. Here a Microsoft Kinect for Xbox 360 was used. It captures users' motions and a FAAST VRPN server (Suma et al., 2011) interprets these motions into gestures and streams them on VRPN. Translational movements (Fig. 2.a) are commanded and controlled by up/down movements of the feet by a walking-in-place (WIP) technique. Movements are processed by mother wavelets to improve real-time user gesture analysis (Mirzaei et al., 2013). Users' natural walking controls the translational movement speed, which means that, the faster one walks, the higher navigation speed. Rotational movements (Fig. 2.b) are commanded when the left/right hand moves above the shoulder: when the left hand is raised, users rotate to the left and conversely when the right hand is raised, they rotate to the right. Rotational speed is controlled by the height of the hand, which means that, the higher the hands, the faster the rotations.

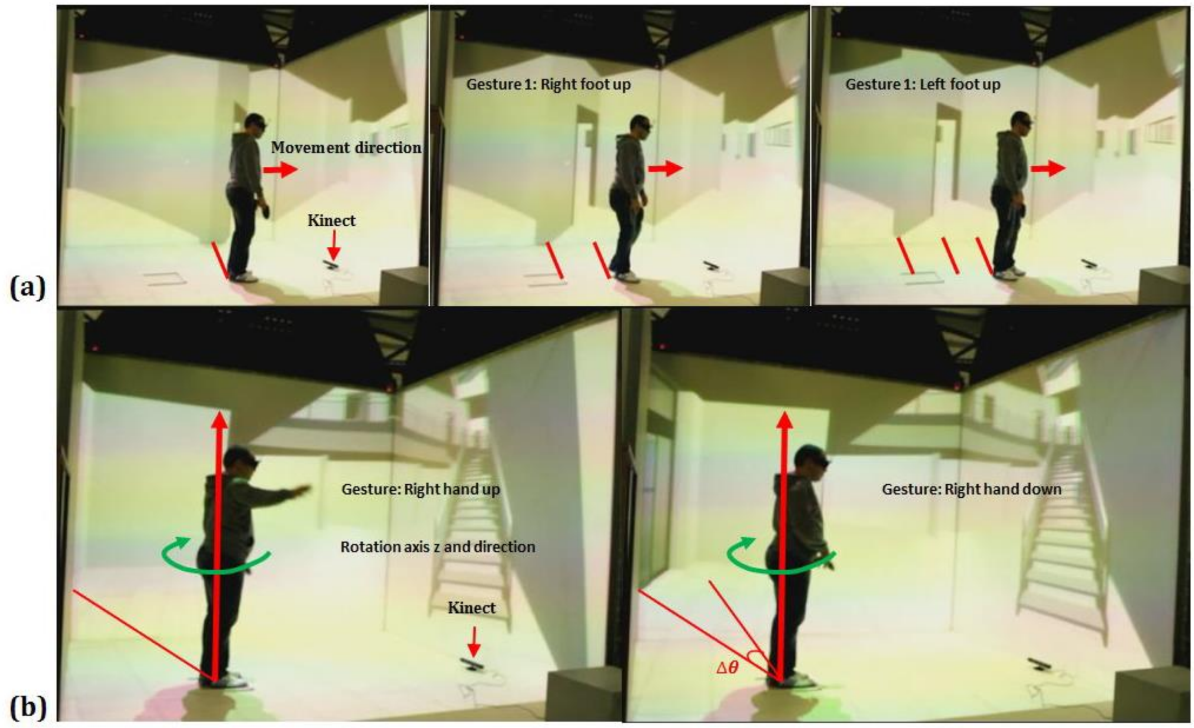

Fig. 2 Navigation based on natural gestures in the CAVE system: (a) walking forward, (b) rotating to the left/right.

3. Experiment 1: effect of the distance from the virtual barrier on cybersickness

The first parameter considered in this study is the distance from a virtual barrier and its effects on the level of cybersickness during navigation. Other parameters such as the navigation speed in the virtual scene are kept constant. This study focuses only on translational movements not to bias results, as rotations are known to have a strong influence on generating sickness (Hu et al., 1988). Translational motion is defined as straight movements from one point to another without any rotation along the path in-between. A translational movement in VEs can be expressed by $V_L = f_L(v, d)$ where independent variables v and d represent the velocity (m.s^{-1}) and the distance (m) from a virtual barrier respectively.

3.1 Experimental design

The virtual environment consisted of a large hall (around 100 meters wide) with walls that were textured with a black and white lined pattern. This pattern was designed to voluntarily exacerbate cybersickness. Four rows of balls were lined up parallel to the virtual wall, indicated by “path 1”, “path 2”, “path 3” and “path 4” in Fig. 3, and were considered as path indicators. Participants navigated along path 1 to path 4 using the DBNI mode. This mode was chosen as we suspected participants to be more familiar with such a device than with NGBNI. Path 1 to path 4 were adjusted $D_1 = 1$m, $D_2 = 2$m, $D_3 = 3$m and $D_4 = 4$m away from the virtual wall, respectively. The path indicators were placed 1.25 m above the ground to help users keep a constant distance from the virtual wall. The real setup is shown in Fig. 4. Navigation speed was kept constant and set to 2m.s^{-1}. Though this value is higher than the average walking speed, we set this speed to facilitate the generation of cybersickness.

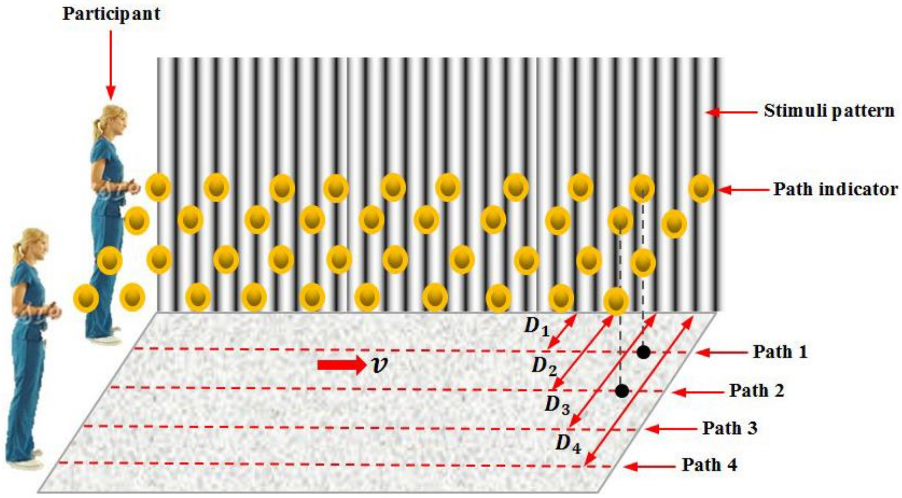

Fig. 3 Experimental design to study the effect of distance on cybersickness.

Fig. 4 Left: virtual environment displayed in the CAVE from the subject’s viewpoint. Right: subject performing the experiment.

The hypothesis formulated for this experiment is that increasing the distance between the virtual barrier and the participants will result in lower cybersickness levels.

3.2 Participants

Ten subjects (8 males and 2 females) participated in the experiment. All participants were recruited among university members (students and staff). There was an individual briefing to give enough information about the test procedure and possible risks before the experiment. A consent form was signed before being exposed to the virtual environment. All subjects participated voluntarily in the experiment (no compensation was given). A demographic questionnaire was filled out by the subjects to find out their background and to evaluate their health condition. From this questionnaire, no health issue was reported by any of the subjects.

3.3 Protocol

Participants were required to navigate along each path in the CAVE. Postural sway was measured prior to the experiment and after each path completion, for 30 seconds each time. We used a TechnoConcept Stabilotest balance board that is able to track the evolution of the ground projection of the subjects’ center of gravity with a sampling frequency of up to 40Hz

(TechnoConcept, 2007). During recording, subjects were asked to stand still on the balance board while fixing a point displayed on a wall. Kennedy's Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) was collected after each path completion from each subject as psychological measurements.

The examiner could stop the experiment if the subjects were not feeling well. In addition, between each navigation round, subjects were able to rest for a few minutes (no more than 5 minutes) if they wished. We did not have any case of serious sickness during the experiment. Note that before the experiment, subjects were asked whether they felt any symptom that could underlie any sickness and whether they were in good condition. The reason for not requesting subjects to fill an SSQ prior to the test lies in its possibility of influencing the subjects' psychological state with regard to exposure to VR, as past research showed that pre-exposure sickness questionnaires could inflate cybersickness scores (Young et al., 2006). All subjects reported being in their usual state of fitness without any symptoms.

The entire experiment lasted around 20 minutes.

3.4 Results

Figure 5 shows the average difference between the postural sway's low frequency (LF) and high frequency (HF) components for each path. Recall that the larger the difference, the more sickness. A one-way ANOVA was conducted to compare the LF-HF difference for each path. Normality checks and Levene's test were carried out and the assumptions met. Results showed a significant effect of the distance to the wall on the difference between LF and HF components, $F(3,36)=4.719$, $p=.007<.05$. Post-hoc comparisons using Student's t-tests revealed that sickness in path 1 ($M=1.34$, $SD=0.12$) was significantly higher than in path 4 ($M=1.13$, $SD=0.11$) ($t(9)=7.27$, $p=.00005<.05$). However, no significant difference was found between path 1 and path 2 ($M=1.23$, $SD=0.16$) ($t(9)=2.08$, $p=.067$), between path 1 and path 3 ($M=1.29$, $SD=0.13$)

(t(9)=0.90, p=.394), as well as between path 2 and path 3 (t(9)=-0.89, p=.398). Last, sickness in path 4 was significantly lower than in path 3 (t(9)=2.92, p=.017<.05) but no significant difference was observed with path 2 (t(9)=1.99, p=.078).

Following the same methodology, the SSQ scores were analyzed. Normality checks and Levene's test were carried out and the assumptions met. A one-way ANOVA was conducted to compare the SSQ scores for each path. Results did not show any significant effect of the distance to the wall on the SSQ scores, F(3,36)=1.394, p=.260>.05 (see Fig. 6). However, cybersickness was observed to decrease on average as subjects navigated further away from the virtual barrier. Therefore, a comparison was done between path 1 (the closest to the wall) and path 4 (the farthest to the wall). A Student's t-test revealed a significant difference between these paths (M_{path1}=288.02, SD_{path1}=109.85; M_{path4}=175.77, SD_{path4}=125.78; t(9)=2.34, p=.044<.05), which indicates that closer distances induces more vection, thus more cybersickness. No significant differences were however detected between the other paths.

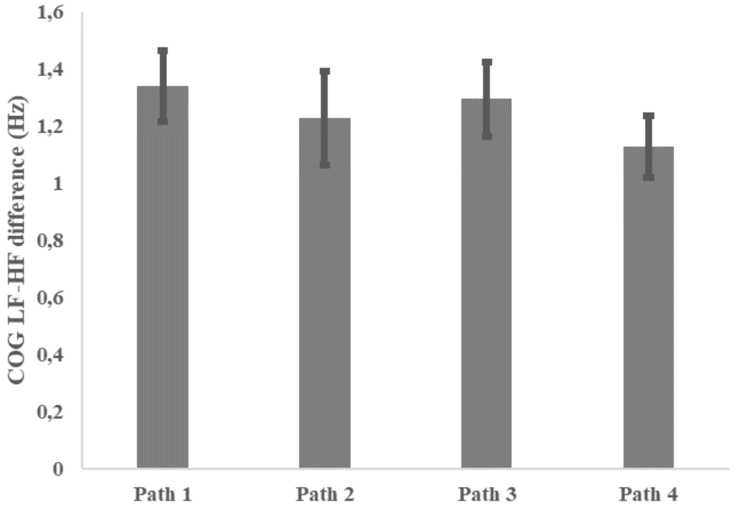

Fig. 5 Difference of the postural sway's low and high frequency components for each path.

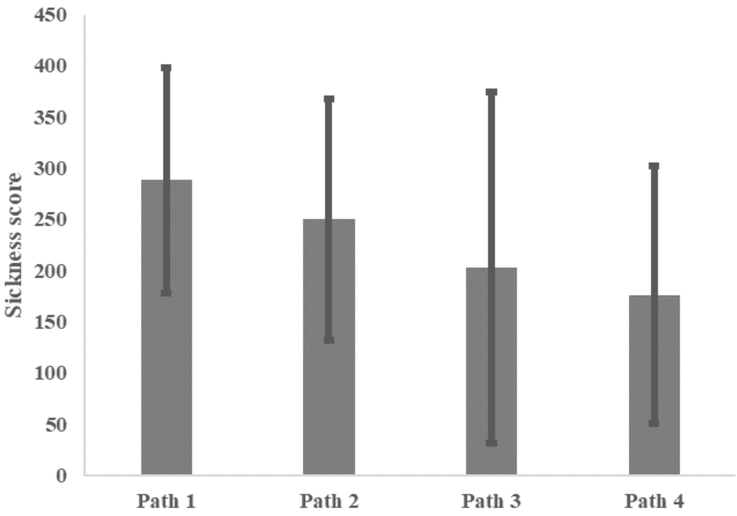

Fig. 6 Sickness scores for each path.

3.5 Discussion

Statistical analysis of the SSQ scores did not reveal any significant effect of distance on cybersickness, whereas postural sway showed opposite results, which suggests that the effect of distance may not be as important as expected. However, from both measures, a significant difference was observed between path 1 and path 4, which may indicate that when navigating close to virtual walls, cybersickness is much stronger. Here, the virtual wall was textured with a pattern that can easily trigger cybersickness. However, in normal virtual environments, such a pattern is not common; therefore, cybersickness might be less important than the one observed in this experiment. Much research studied the effect of such a pattern on eye movement, through the well-known optokinetic reflex, albeit mostly applied to rotational movements (Nooij et al., 2017). However, we focused here on translational movements only and the required task was not to follow the pattern but navigation paths. Interestingly, the evolution of the LF-HF differences did not follow exactly the same pattern as for the SSQ scores, as a slight increase was observed on average between path 2 and path 3. Further studies with more participants should be carried out to confirm these findings and to determine their exact cause.

Our findings can also be explained by motion parallax. By definition, the farther away a subject is from an object (here a virtual wall), the slower he/she perceives motion along that object. Therefore, from a perceptual point of view, as speed was kept constant whatever the distance from the virtual wall was, the farther away from the barrier subjects navigated, the slower motion was perceived, which contributed to reduce cybersickness effects. As a result, one suggestion to alleviate cybersickness effects would be to adjust motion speed as a function of the distance from virtual obstacles. Another possibility could be to deform locally the geometry of the surrounding environment to lower vection, as proposed for example in (Lou & Chardonnet, 2019).

4. Experiment 2: comparison between DBNI and NGBNI

The effect of the navigation interface is studied in this experiment. Two navigation interfaces, DBNI (Flystick) and NGBNI (WIP with gesture recognition using a Kinect), described in Section 2, are selected to represent the two main categories of navigation interfaces. When attempting to walk in a natural way in a virtual environment, the motion pattern perceived by sensory afferents matches the proprioceptive pattern, which in turn creates less sensory conflict at the onset and the cessation of the sensory rearrangement (Chance et al., 1998). For that reason, it makes sense to draw up the hypothesis that natural gesture-based navigation interfaces will provoke less cybersickness compared to DBNI.

4.1 Experimental design

As in the previous study, this experiment consisted in moving along a straight path in a large virtual environment. The environment was the same as in the previous experiment, except that only one row of yellow balls was displayed parallel to the wall of the hall. The distance of the path to the virtual wall was set to 4 meters to stay consistent with the results of Experiment 1. Navigation speed was kept the same as in Experiment 1: 2m.s^{-1}.

4.2 Participants

Seventeen subjects (12 males and 5 females) among university members were selected to participate in the experiment. There was an individual briefing to give enough information about the test procedure and possible risks before each experiment. A consent form was signed before being exposed to the virtual environment. All subjects participated voluntarily in the experiment (no compensation was given). A demographic questionnaire was filled out by the subjects to know their background and to evaluate their health condition. From this questionnaire, no health issue was reported by any of the subjects. Additionally, all subjects reported being in their usual state of fitness without any symptom of sickness.

4.3 Protocol

The experiment was carried out as follows:

1. The postural sway of each subject was recorded for 30s before the experiment.
2. Subjects were invited to enter the CAVE and to navigate along the path, either with NGBNI or with DBNI. The navigation interface was attributed randomly. At the end of the path, subjects were removed from the CAVE.
3. The postural sway of each subject was recorded again for 30s.
4. Subjects were asked to fill out an SSQ.
5. The experiment was repeated with the other interface on another day to prevent accumulation effects.

The examiner could stop the experiment if the subjects were not feeling well. We did not have any case of serious sickness during the experiment.

The entire experiment lasted around 10 minutes.

4.4 Results

Figure 7 shows the average difference between the postural sway's LF and HF components for each interface type. As in the previous experiment, the larger the difference, the more sickness. A Student's t-test was conducted to compare the LF-HF difference for each interface. Normality checks and Levene's test were carried out and the assumptions met. Results revealed that the difference between LF and HF components was significantly higher with DBNI (M=1.61, SD=0.10) than with NGBNI (M=1.22, SD=0.14), t(16)=9.74, p<.001, which suggests that DBNI provokes more cybersickness than NGBNI.

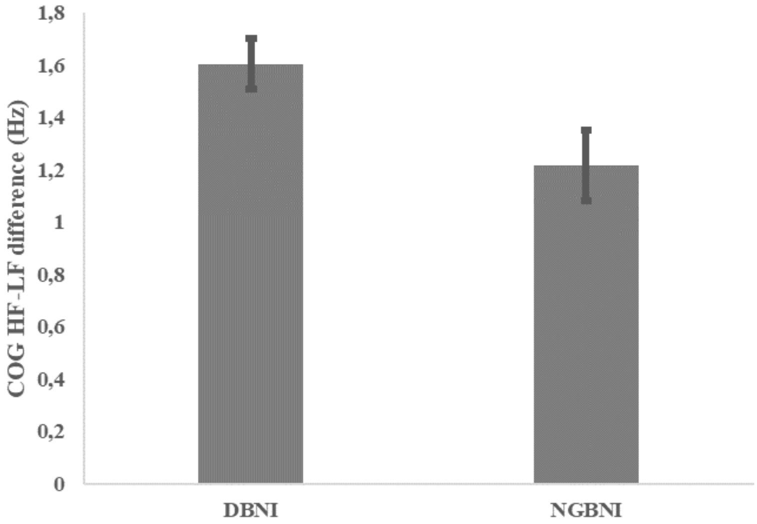

Fig. 7 Difference of the postural sway's low and high frequency components for DBNI and NGBNI.

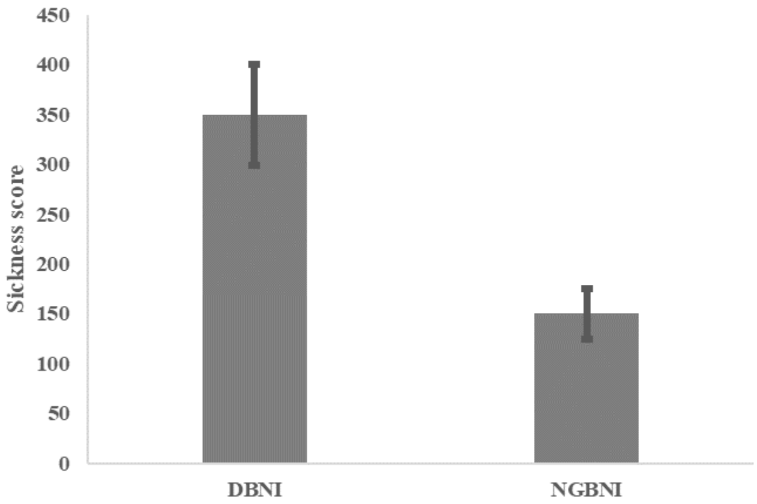

Fig. 8 Sickness scores for DBNI and NGBNI.

Similarly, a Student's t-test was conducted to compare the SSQ scores for each interface. Normality checks and Levene's test were carried out and the assumptions met. The sickness score associated with DBNI (M=350.0, SD=50.63) was significantly higher than with NGBNI (M=150.0, SD=25.63), t(16)=14.53, p<.001 (see Fig. 8), indicating that DBNI does generate more cybersickness than NGBNI.

4.5. Discussion

A significantly smaller LF-HF difference was observed with NGBNI than with DBNI, which means that less cybersickness was induced by natural navigation interfaces. This result was confirmed by significantly lower cybersickness scores for NGBNI than for DBNI. NGBNI provide thus better navigation experience to users in terms of cybersickness compared to DBNI.

Several reasons can explain these results. First, when using DBNI devices, subjects hardly moved, therefore the likeliness of the sensory conflict to occur was much higher. Whereas, when using NGBNI devices, subjects needed to move their body, which stimulated the vestibular system and therefore led to less sensory conflict. As mentioned above, with NGBNI, the motion pattern perceived by sensory afferents is closer to the expected pattern. The navigation technique that we designed for NGBNI combines several gestures: walking in place for translations and arm gestures for rotations. However, past literature found walking in place not to be as effective as real walking, as it generates discomfort and physical fatigue (Usoh et al., 1999). In fact, though these methods are categorized as natural, their naturalness is questionable (Norman, 2010) and users are required to learn the right gestures. One issue with natural gesture-based interfaces lies in gesture recognition algorithms that may not be robust enough and thus lead to wrong interaction commands. Then, despite their lack of naturalness, NGBNI may still appear more natural to navigate than DBNI for users who are not familiar with VR technologies, especially joystick-based interfaces, since natural interfaces imply less cognitive load (Valli, 2008). It may then induce less cybersickness, as past research found that users under high cognitive load usually report higher levels of sickness (Pausch & Crea, 1992). Taking into consideration users' profiles may be an interesting clue for selecting the right navigation paradigm and lowering cybersickness.

5. Conclusion and future work

Two experiments were performed to study the influence of two navigation parameters on cybersickness: distance from a virtual barrier and the interface used to navigate (natural gesture-based or device-based). We observed that: (i) navigating close to a virtual barrier seems to generate more cybersickness than being far away from it, (ii) using natural gesture-based interaction interfaces leads to less cybersickness than device-based interfaces.

From these results, several suggestions can be proposed to lower cybersickness. First, an automatic navigation speed controller can be derived to maintain low cybersickness levels and allow enhanced user experience. With such a controller, the navigation speed can be automatically adjusted depending on the situations subjects encounter. For instance, it can be calculated as a function of the distance from virtual obstacles. As an example, when subjects navigate close to a virtual barrier, speed decreases automatically; conversely, as they move away from the obstacle, speed increases progressively. Second, navigation systems could be smarter by adapting navigation to the users' profile. This would lead to customized virtual reality. These ideas will be explored in future studies.

Some VR designers recommend setting constant navigation speeds, though past research showed that one possibility to alleviate cybersickness effects is to modify speed depending on the surrounding environment (Argelaguet, 2014), i.e., even though speed is not constant, cybersickness can be lowered, as long as the speed control is well designed.

In the first experiment, a joystick-based technique (DBNI) was solely used as we considered this technique to be much more widely employed in virtual reality than natural gesture-based techniques (NGBNI). However, it could be interesting to see whether NGBNI techniques could lead to results similar to those presented here. We keep this issue for a future study.

Here only translational movements were considered. Rotational movements should also be studied. However, a huge piece of work already exists on this topic, as it is well known that rotational motions are prone to sickness. Past research revealed that the effect of rotational velocity on cybersickness has a Gaussian distribution, with a mean located at $\omega = 60°.s^{-1}$ (Hu et al., 1988). Therefore angular velocities lower than $60°.s^{-1}$ should be selected, whatever the distance from a virtual obstacle.

We studied the effect of only two navigation parameters on cybersickness. However, many other factors should be taken into account such as the inter-pupillary distance, the system latency, the field of view, etc. These parameters cannot be studied all at once; however, we intend to focus on some of them, such as the inter-pupillary distance, to derive strategies to reduce cybersickness. We also believe that, as proposed above, taking into consideration the users' state and profile better, and thus their physiological characteristics, in real time can lead to enhanced user experience.

References

Akiduki, H., Nishiike, S., Watanabe, H., Matsuoka, K., Kubo, T., & Takeda, N. (2003), 'Visual-vestibular conflict induced by virtual reality in humans', *Neuroscience Letters, 340(3),* 197-200. doi: 10.1016/S0304-3940(03)00098-3.

Argelaguet Sanz, F. (2014), Adaptive Navigation for Virtual Environments, *in IEEE Symposium on 3D User Interfaces*, pp. 91–94. doi: 10.1109/3DUI.2014.7027325.

Bonato, F., Bubka, A., Palmisano, S. A., Phillip, D. & Moreno, G. (2008), 'Vection change exacerbates simulator sickness in virtual environments', *Presence, 17(3),* 283-292. doi: 10.1162/pres.17.3.283.

Bos, J. E., Bles, W., & Groen, E. L. (2008), 'A theory on visually induced motion sickness', *Displays, 29(2),* 47-57. doi: 10.1016/j.displa.2007.09.002.

Bowman, D. A., Kruijff, E., LaViola, J. J., & Poupyrev, I. (2004), *3D User Interfaces: Theory and Practice*, Addison Wesley Longman Publishing Co., Inc., Redwood City, CA, 2004

Buker, T. J., Vincenzi, D. A., & Deaton, J. E. (2012), 'The Effect of Apparent Latency on Simulator Sickness While Using a See-Through Helmet-Mounted Display: Reducing Apparent Latency With Predictive Compensation', *Human Factors: The Journal of the Human Factors and Ergonomics Society, 54(2),* 235-249. doi: 10.1177/0018720811428734.

Chance, S. S., Gaunet, F., Beall, A. C., & Loomis, J. M. (1998), 'Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration', *Presence, 7(2),* 168-178. doi: 10.1162/105474698565659.

Chardonnet, J.-R., Mirzaei, M. A., & Merienne, F. (2017), 'Features of the Postural Sway Signal as Indicators to Estimate and Predict Visually Induced Motion Sickness in Virtual Reality', *International Journal of Human-Computer Interaction, 33(10),* 771-785. doi: 10.1080/10447318.2017.1286767.

Chen, W., Plancoulaine, A., Férey, N., Touraine, D., Nelson, J., & Bourdot, P. (2013), 6DoF navigation in virtual worlds: comparison of joystick-based and head-controlled paradigms, *in Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology (VRST '13),* pp. 111-114. doi: 10.1145/2503713.2503754.

Cobb, S. (1999), 'Measurement of postural stability before and after immersion in a virtual environment', *Applied Ergonomics, 30(1),* 47-57. doi: 10.1016/S0003-6870(98)00038-6.

Coomer, N., Bullard, S., Clinton, W., & Williams-Sanders, B. (2018), Evaluating the effects of four VR locomotion methods: joystick, arm-cycling, point-tugging, and teleporting, *in Proceedings of the 15th ACM Symposium on Applied Perception (SAP '18)*. doi: 10.1145/3225153.3225175.

Farmani, Y., & Teather, R. (2018), Viewpoint Snapping to Reduce Cybersickness in Virtual Reality, *in Proceedings of Graphics Interface 2018,* pp. 159-166. doi: 10.20380/GI2018.21.

Hsiao, E. W., Widdowson, C., Merrill, C., Becerra, I. (2018), Effect of Acceleration on Simulator Sickness in Virtual Reality, *in Undergraduate Research Symposium 2018,* University of Illinois.

Hu, S., Koch, K. L., Vasey, M. W., & Stern, R. M. (1988), ‘Motion Sickness and Electrogastrographic Activity As a Function of Speed of Rotation of an Optokinetic Drum’, *Psychophysiology*, vol. 25, p. 456.

Kemeny, A. (2014), From driving simulation to virtual reality, *in Proceedings of Virtual Reality International Conference*. doi: 10.1145/2617841.2620721.

Kemeny, A., Colombet, F., & Denoual, T. (2015), How to avoid simulation sickness in virtual environments during user displacement, *in The Engineering Reality of Virtual Reality 2015*, volume 9392, pp. 9392:1–9392:9. doi: 10.1117/12.2077080.

Kennedy, R., & Stanney, K. (1996), ‘Postural instability induced by virtual reality exposure: development of a certification protocol’, *International Journal of Human-Computer Interaction, 8(1)*, 25-47. doi: 10.1080/10447319609526139.

Kennedy, R. S., Drexler, J. M., Compton, D. E., Stanney, K. M., Lanham, D. S., Harm, D. L. (2003), ‘Configural scoring of simulator sickness, cybersickness and space adaptation syndrome: similarities and differences’, *in Virtual and Adaptive Environments: Applications, Implications, and Human Performance*, 247-278.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993), ‘Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness’, *The international Journal of Aviation Psychology, 3(3),* 203-220. doi: 10.1207/s15327108ijap0303_3.

Keshavarz, B., Riecke, B. E., Hettinger, L. J., & Campos, J. L. (2015), ‘Vection and visually induced motion sickness: how are they related?’, *Frontiers in Psychology, 6,* 472. doi: 10.3389/fpsyg.2015.00472.

Kolasinski, E. M. (1995), Simulator Sickness in Virtual Environments, (1027), Technical report. Alexandria, VA: U.S. Army Research Institute.

LaValle, S. (2017), *Virtual Reality,* Cambridge University Press.

LaViola, Jr., J. J. (2000), ‘A discussion of cybersickness in virtual environments’, *SIGCHI Bull., 32(1),* 47-56. doi: 10.1145/333329.333344.

Lin, J. W., Duh, H. B. L., Parker, D. E., Abi-Rached, H. & Furness, T. A. (2002), Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment, *Proceedings IEEE Virtual Reality 2002,* pp. 164-171. doi: 10.1109/VR.2002.996519.

Lloarch, G., Evans, A., & Blat, E. (2014), Simulator sickness and Presence using HMDs: comparing use of a game controller and a position estimation system, *in VRST’14 Proceedings of the 20th ACM Symposium on Virtual Reality Software,* pp. 137-140. doi: 10.1145/2671015.2671120.

Lo, W. T., & So, R. H. Y. (2001), ‘Cybersickness in the presence of scene rotational movements along different axes’, *Applied Ergonomics, 32(1),* 1-14, doi: 10.1016/S0003-6870(00)00059-4.

Lou, R., & Chardonnet, J.-R. (2019), Reducing Cybersickness by Geometry Deformation, *in IEEE Virtual Reality (VR),* pp. 1058-1059. doi: 10.1109/VR.2019.8798164.

Mestre, D. (2014), Evaluation of navigation interfaces in virtual environments. *Proceedings of SPIE - The International Society for Optical Engineering, 9012*. doi: 10.1117/12.2042141.

Mirzaei, M. A., Chardonnet, J.-R., Père, C., & Merienne, F. (2013), Improvement of the real-time gesture analysis by a new mother wavelet and the application for the navigation inside a scale-one 3D system, *in IEEE International Conference on Advanced Video and Signal-Based Surveillance,* pp. 270-275. doi: 10.1109/AVSS.2013.6636651.

Murata, A. (2004), ‘Effects of duration of immersion in a virtual reality environment onpostural stability’, *International Journal of Human-Computer Interaction, 17(4),* 463-477. doi: 10.1207/s15327590ijhc1704_2.

Nooij, S. A. E., Pretto, P., Oberfeld, D., Hecht, H., & Bülthoff, H. H. (2017), 'Vection is the main contributor to motion sickness induced by visual yaw rotation: Implications for conflict and eye movement theories', *PLoS ONE, 12(4)*. doi: 10.1371/journal.pone.0175305.

Norman, D. A. (2010), 'Natural user interfaces are not natural'. *Interactions, 17(3)*, 6-10. doi: 10.1145/1744161.1744163.

Oman, C. M. (1990), 'Motion sickness: a synthesis and evaluation of the sensory conflict theory', *Canadian Journal of Physiology and Pharmacology, 68(2)*, 294-303. doi: 10.1139/y90-044.

Palmisano, S., Mursic, R., & Kim, J. (2017), 'Vection and cybersickness generated by head- and display motion in the Oculus Rift', *Displays, 46*, 1-8. doi: 10.1016/j.displa.2016.11.001.

Pausch, R., & Crea, T. (1992), 'A Literature Survey for Virtual Environments: Military Flight Simulator Visual Systems and Simulator Sickness'. *Presence, 1(3)*, 344-363. doi: 10.1162/pres.1992.1.3.344.

Plouzeau, J., Chardonnet, J.-R., & Merienne, F. (2018), Using cybersickness indicators to adapt navigation in virtual reality: a pre-study, *in IEEE Virtual Reality*, pp. 661-662. doi: 10.1109/VR.2018.8446192.

Razzaque, S., Swapp, D., Slater, M., Whitton, M. C., & Steed, A. (2002), Redirected walking in place, *in Proceedings of the workshop on Virtual environments 2002 (EGVE '02)*, pp. 123-130. doi: 10.2312/EGVE/EGVE02/123-130.

Reason, J. T., & Brand, J. J. (1975), *Motion sickness*, Academic Press, London.

Riccio, G. E., & Stoffregen, T. A. (1991), 'An ecological theory of motion sickness and postural instability', *Ecological psychology, 3(3)*, 195-240. doi: 10.1207/s15326969eco0303_2.

Sharples, S., Cobb, S., Moody, A., & Wilson, J. R. (2008), ‘Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems’, *Displays, 29(2)*, 58-69. doi: 10.1016/j.displa.2007.09.005.

Slater, M., Steed, A., & Usoh, M. (1995), The Virtual Treadmill: A Naturalistic Metaphor for Navigation in Immersive Virtual Environments, *in Virtual Environments ’95*, pp. 135-148. doi: 10.1007/978-3-7091-9433-1_12.

So, R. H. Y., Lo, W. T., & Ho, A. T. K. (2001), ‘Effects of Navigation Speed on Motion Sickness Caused by an Immersive Virtual Environment’, *Human Factors: The Journal of the Human Factors and Ergonomics Society, 43(3)*, 452-461. doi: 10.1518/001872001775898223.

Stauffert, J.-P., Niebling, F., & Latoschik, M. E. (2018), Effects of Latency Jitter on Simulator Sickness in a Search Task, *in IEEE Virtual Reality*, pp. 121-127. doi: 10.1109/VR.2018.8446195

Suma, E. A., Lange, B., Rizzo, A., Krum, D. M., & Bolas, M. (2011), Faast: The flexible action and articulated skeleton toolkit, *in IEEE Virtual Reality Conference (VR)*, pp. 247-248. doi: 10.1109/VR.2011.5759491.

TechnoConcept (2007), ‘Techno-concept balance board manual, Notice Logiciel SabotSoft’.

Treisman, M. (1977), ‘Motion sickness : an evolutionary hypothesis’, *Science, 197(4302)*, 493-495. doi: 10.1126/science.301659.

Usoh, M., Arthur, K., Whitton, M. C., Bastos, R., Steed, A., Slater, M., & Brooks, Jr., F. P. (1999), Walking > walking-in-place > flying, in virtual environments, *in Proceedings of the 26th annual conference on Computer graphics and interactive techniques (SIGGRAPH '99)*, pp. 359-364. doi: 10.1145/311535.311589.

Valli, A. (2008), ‘The design of natural interaction’. *Multimedia Tools and Applications*, 38, 295-305. doi: 10.1007/s11042-007-0190-z.

Wilson, M. L. (2016), ‘The Effect of Varying Latency in a Head-Mounted Display on Task Performance and Motion Sickness’, PhD thesis, Clemson University.

Young, S. D., Adelstein, B. D., & Ellis, S. R. (2006), Demand Characteristics of a Questionnaire Used to Assess Motion Sickness in a Virtual Environment, *in IEEE Virtual Reality Conference (VR 2006)*, pp. 97-102. doi: 10.1109/VR.2006.44.