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A Semiautomatic Navigation Interface to Reduce Visually Induced Motion Sickness in Virtual Reality

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ABSTRACT

Navigation in a real environment is a common task that human beings conduct easily and subconsciously. However transposing this task in virtual environments (VEs) remains challenging due to input devices and techniques which may induce cybersickness and frustration among users. Considering the well-described sensory conflict theory, we present a semiautomatic navigation method based on path planning algorithms, aiming at reducing the generation of conflicted signals that may confuse the central nervous system (CNS). We carried out experiments where participants were asked to navigate in a VE equipped with an HTC Vive headset. Compared to joystick-based navigation which induces unsmoother and jerkier movements in VEs, objective and subjective evaluations indicated that semiautomatic navigation was more effective and accurate and enabled more concentration and immersion, leading to a significant reduction of visually-induced cybersickness.

Index Terms: Human-centered computing—Virtual reality—Walkthrough evaluations; Human-centered computing—User interface design—Interaction devices

1 INTRODUCTION

In response to the quickly increasing virtual reality market for practical application, navigation interfaces in virtual environments (VEs) have been recognized as the most fundamental feature to provide user satisfaction, sense of presence, reduced cybersickness and entertainment when designing a product, a building, or when showing reconstructed places to general public [9]. Navigation is paramount in VEs for two primary reasons: first, navigation is the most common and universal way enabling users to interact with objects and explore VEs as if in a physical world; second, navigation is often performed to support another task, for example, pick up treasures, fight enemies, and obtain spatial information [11] .

To achieve successful navigation in VEs, appropriate navigation devices and techniques should be intuitive and should allow users a realistic perception of VEs. For instance, devices such as joysticks or head orientation tracking based devices using gyro in virtual reality headsets are widely used to travel in VEs. This kind of travel devices is easy to use and effective for novice users to control movements in VEs. However, joysticks are unable to provide smooth movements towards a target location but allow to move suddenly and irregularly. Such travel technique fails to provide natural movements and is more likely to induce cybersickness [19], resulting from serious discrepancies between visual information and the vestibular system.

A path drawing technique was designed to navigate in virtual 3D spaces by Igarashi et al. [8]. This method allows users to draw the desired path with a free stroke, then the system automatically projects the stroke onto the walking surface to generate the final moving path. The avatar and the view point move to the target position along the tangents of the path with a controllable speed. A user study found that path drawing is preferred and more intuitive compared to both driving and flying navigation methods. In addition, since the movements can be easily controlled by drawing the path, users do not have to hold on a controller's button all the time, thus making it possible for novice users to focus on other tasks during navigation [15].

Instead of drawing a path, automatic path planners from the humanoid robotics field which has focused on the evolution of humanoids in real environments [14] is also proved to be an efficient method. Yao et al. [21] introduced the application of path planing to travel in VEs and they managed to control a virtual human motion with an improved A* algorithm, thereby allowing the system to plan automatically an optimal path from the starting point to the target point with the intention of committing a specific task such as *search* or *maneuvering*. Thanks to boosted computational performance with GPUs, the algorithm can also be extended to real-time applications used for multi-agent travel in VEs [16]. A practical application is navigation in very constrained environments such as radioactive environments in order to protect users from being harmed under high radiation. Liu et al. applied path-planning algorithms into a virtual-real mixed simulation program to provide a minimum dose navigational approach [12]. In addition, further research on the application of *Dijsktra's algorithm* and *RRT* algorithm* (two other path-planning algorithms) were implemented, and the results were compared so as to verify the effectiveness and feasibility of path-planning algorithms in VEs [2]. This work was developed with path-planning algorithms to make task optimization and evaluation intuitive, effective and secure, but they were not designed as a travel interface for first-person applications to address cybersickness.

1.1 Contributions

With the intention of developing a navigation interface to provide better user experience and reduce cybersickness, we present in this paper a new semiautomatic technique to navigate in immersive VEs. We combine path planning algorithms from humanoid robotics and first-person navigation in VEs where psycho-physiological parameters are of major concern. The novelties and contributions of the proposed travel techniques include the following aspects:

- Design a semiautomatic navigation method: we propose to integrate real-time automatic navigation through path planning algorithms to allow smooth and optimized travels, with the ability for users to manually adjust the path with a gaze-directed navigation method, which provides more freedom to modify the generated path in VEs, depending on the task to be performed. The design of our navigation method will be presented in Sect. 2.
- Analyze the effectiveness and user satisfaction of our proposed navigation technique. In most cases, semiautomatic navigation outperforms joystick-based navigation especially regarding cybersickness, as shown in Sect. 4.

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2 DESIGN OF SEMIAUTOMATIC NAVIGATION

Currently, many navigation interfaces have been developed with the intention of enhancing user comfort but cybersickness is still an inherent problem to be overcome in virtual reality [5]. Considering the sensory conflict theory, the problem becomes: can we design a navigation interface that reduces the conflicted signal as much as possible? In order to answer this question, we designed the semiautomatic navigation system and we hypothesized that the user should suffer from less cybersickness.

2.1 Semiautomatic Navigation

The original purpose of semiautomatic navigation is that a virtual reality system provides basic control rules and dynamics during navigation while still allowing users to control the system if necessary [6]. In this work, a semiautomatic navigation interface was developed based on an automatic path planner together with a gaze-directed technique to allow to manually modify the generated path if needed. Among manual navigation techniques, we chose the gaze-directed technique as it is easy to use while being close to real situations where before travelling, we usually look in the target direction.

One general issue of gaze-directed navigation is that it couples gaze direction and travel direction, which means that users cannot look in one direction but move to another direction simultaneously. However, considering real life experience that people may look in a direction other than their travel direction during walking, cycling, or driving in the physical world, the introduced automatic path planner fills up such deficiency. In addition, if a complete 3D motion (e.g., “flying”) is enabled in VEs, the gaze-directed technique has to tackle two problems: a) users may navigate up and down when they travel in a horizontal plane since it is difficult to keep the head in the same level precisely. b) even if users manage to control the head direction, it is also awkward to correct the navigation trajectory vertically up or down by looking straight up or down.

In order to overcome these two deficiencies of the gaze-directed technique, we add a path planner that can control the trajectory and avoid the “up or down” effect. A user firstly specifies a target to the VE platform, the system reads the current states of the avatar position and orientation and the destination. The path-planning algorithm connects the avatar position to the target position with the shortest trajectory using the A* path planning algorithm (see Tiwari et al. [17] for a detailed explanation of A*) by taking into account environmental constraints simultaneously. However, the original trajectory generated by the A* algorithm has only C^0 continuity which is unnatural and very similar to the path generated from a joystick controller. In order to smoothen the trajectory, we can implement numerical methods like clothoid curves, polynomial curves and Bézier curves to define the final shape of the path, but we choose Bézier curves as in Equation 1, because it has the lowest computational cost [7],

$$\mathbf{B}(t) = \sum_{k=0}^{n} P_k \binom{n}{k} (1-t)^{n-k} t^k \qquad (1)$$

where n is an integer related to the degree of the Bézier curve, P_k is the selected control point from the original A* trajectory, and t is a parameter, $t \in [0,1]$. In a real case, the control point computed on the raw path generated from the A* algorithm is given in Equation 2,

$$\begin{cases} P_0 = T_i + l_1 \frac{T_{i-1}-T_i}{||T_{i-1}-T_i||} \\ P_1 = T_i + l_2 \frac{T_{i-1}-T_i}{||T_{i-1}-T_i||} \\ P_2 = T_i + l_3 \frac{R-T_i}{||R-T_i||} \\ P_3 = T_i + l_2 \frac{T_{i+1}-T_i}{||T_{i+1}-T_i||} \\ P_4 = T_i + l_1 \frac{T_{i+1}-T_i}{||T_{i+1}-T_i||} \end{cases} \qquad (2)$$

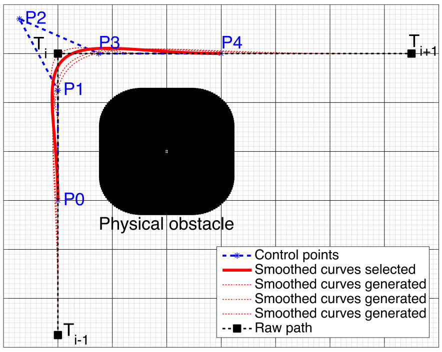


Figure 1: Application of a 4^{th} degree ($n = 4$) Bézier curve to smoothen an intersection. The thick red line is the selected trajectory.

where, as shown in Fig. 1, T_{i-1}, T_i and T_{i+1} are the raw path points coming from the path planner; P_0, P_1, P_3 as well as P_4 are set to lie in the raw path; l_1 is the distance from T_i to P_0 and P_4; l_2 is the distance from T_i to P_1 and P_3; l_3 is the distance along the angular bisector (obtuse angle) of the intersection; R is a point on the angular bisector. Here the hyper-parameters are l_1, l_2 and l_3, but since l_1 and l_2 lie in the same direction, to simplify, we can define a new hyper-parameter r,

$$r = \frac{l_1}{l_2} \qquad (3)$$

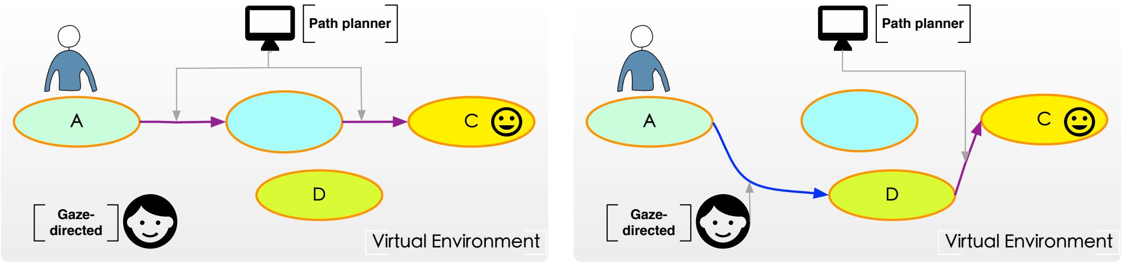
and if we fix l_2, the final hyper-parameters become r and l_3, which makes it easier to control the shape of the smoothed path.

Fig. 2 presents four different examples for the application of the semiautomatic navigation technique. The user has to navigate to position C from position A, and in the simplest case, if there is no specific reason motivating her/him to pass through position D, the path from the path planner would be the best choice. On the other hand, one user may not want to follow the trajectory from the path planner but to travel with a personalized way where the gaze-directed technique provides a natural interaction between the VE and the user. For example in a game, users want to pick up treasures along the way “$A \rightarrow D \rightarrow C$” instead of “$A \rightarrow B \rightarrow C$” in the VE, so the gaze-directed technique enables them to change the motion path towards another position D, which works as a supplementary to the automatic motion planner. Finally, the user will be translated successfully to the destination with the trajectory from either the path planner or the gaze-directed method, both providing smooth trajectories.

3 USER STUDY

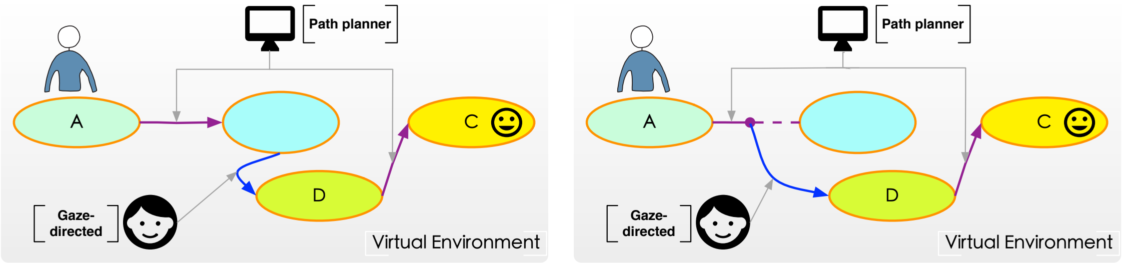
3.1 Travel Techniques Setup

All the tests for this study were run using an HTC Vive head-mounted display. The travel techniques were separated into two groups: a control group and an experimental group. The control group was set to be a performance baseline for our new strategy. It is worth noting that here we introduced the idea of two groups but we just regarded them as a way to discriminate current travel techniques and our proposed travel technique. Concerning the sensory conflict theory, tests were conducted to show that the control group shall result in more cybersickness whereas the experimental group shall lead to less cybersickness by avoiding unnecessary and noisy movement.



(a) The user simply navigates from A to C by following the path generated from the path planner during the whole process, passing position B. This may happen when the user does not have to conduct activities in position D.

(b) The user firstly navigates to position D with gaze-directed technique to conduct a task since B is not the desired position, while she/he can activate the path planner again in the later stage to go to position C .



(c) The user firstly arrives at position B with the path planner but then she/he can go to position D with the gaze-directed method to perform a task; finally she/he uses the path planner to go to position C.

(d) The user initially decides to go with the default path planner but she/he changes her/his mind before arriving at position B, so the gaze-directed technique enables her/him to move to position D. After finishing the task in D, she/he moves to C with the path planner.

Figure 2: Semiautomatic travel technique to navigate from position A to position C in a VE: the purple line is the trajectory generated from the path planner while the blue line is the trajectory generated from the gaze-directed technique. A, B, C and D are arbitrary positions of the walkable surface in the VE.

Accordingly, joystick-based navigation, which was considered to be an unnatural navigation technique and tends to induce more cybersickness, was selected as the control group. On the other hand, our semiautomatic control technique was designed to provide more user comfort and thus was selected as the experimental group.

3.1.1 Control group

Joystick-based navigation was implemented to enable users to control movements in the VE, i.e., navigating in both translational and rotational directions. Note that the position and orientation of the joystick was independent of that of the user, meaning that the user's position and orientation in the physical world must be initialized to be consistent with that in the VE. The maximal speed was set to $2m.s^{-1}$ but the actual speed depended on the user's input from the controller.

3.1.2 Experimental group

As explained in Sect. 2, the semiautomatic navigation was designed by combining the advantage of a path planner and gaze-directed navigation. The path planner we designed was implemented on top of NavMeshAgent which is a navigation mesh agent implemented with the A* algorithm in Unity3D, while the implementation of the gaze-directed technique was based on an open source library, VRTK[1]. As mentioned, the user has two options: navigation following a smooth path towards the desired position, or navigation using the gaze-directed technique to modify the default if necessary. When the user presses the trigger button of the HTC Vive handheld controller, she/he will be translated along the generated path, but if the user touches the touchpad of the controller, she/he will be translated to the direction of gaze. The maximal speed was also set to be $2m.s^{-1}$, but the real speed depended on how much the button was pressed. The generated path is displayed to the users so that they can decide whether following the generated path or modifying it with the gaze-directed technique.

3.1.3 Hypotheses

In order to assess the performance of the semiautomatic navigation method, we hypothesized that

H1 Compared to joystick-based navigation, our semiautomatic travel technique is much more efficient and provides more immersion since it enables users to concentrate on the assigned task instead of learning how to use the navigation interface.

H2 The semiautomatic travel technique can help users find an optimized and smoothed path, thereby significantly alleviating cybersickness, while joystick-based navigation normally translates users with irregular and jerky trajectories resulting in increased sensory conflict.

3.2 Participants

We invited 13 participants including 4 females (mean age 25.83, SD=4.58) to the experiment. Before the experiment, a pre-exposure

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[1] https://vrtoolkit.readme.io

questionnaire (Q1) was filled in to get a better insight of the participants' background and health condition. From this questionnaire, all subjects had normal or corrected-to-normal vision and reported no disorders or unusual circumstances with respect to their hearing or balancing. During the experiment, one participant dropped out due to strong cybersickness, and the corresponding results were not taken into account for statistical analyzis. None of them had experienced VR before the experiment.

3.3 Task Design and Experimental Procedure

The experiments were carried out in a large space free of any obstacles to make sure there was no interference that could affect user experience. The virtual environment, implemented in Unity3D, was a 3D model of a building including many office rooms where the participants were asked to explore and pick up a total of 30 coins scattered in different places as fast as possible inside the VE. The coins had to be collected in a specific order: the coins were numbered from 1 to 30, and the participants had to catch them in an ascending order. To avoid biased results from users' evaluation, the two navigation techniques were presented in a random order. The evaluation of user experience and cybersickness was conducted with the following two methods.

3.3.1 Subjective evaluation

Participants were given a training on the two different navigation interfaces and they were allowed to stay a given period in the virtual environment before conducting the experiment. Each session of the experiment ended with the simulator sickness questionnaire (SSQ, Q2) to report cybersickness [10], and a brief questionnaire (Q3, to evaluate each navigation method in terms of efficiency, likability, accuracy, learnability, immersion, naturality, consistence and concentration) as a feedback about general impressions on the navigation method just used. It is worth noting that here Q3 was designed mainly according to some quality factors from the work of Bowman et al. [1] to measure the navigation interfaces; the factors include the speed (appropriate velocity or the total time spent to complete the task), accuracy (proximity to the desired target), spatial awareness (the participant's implicit knowledge of her/his position and orientation within the environment during and after travel), ease of learning (the ability of a novice user to use the technique), ease of use (the complexity or cognitive load of the technique from the participant's point of view), and presence (the participant's sense of immersion or "being within" the environment). We extracted some questions from the Witmer-Singer presence questionnaire [20] in order to help participants evaluate the navigation interfaces from different perspectives.

3.3.2 Objective evaluation

The questionnaires represent a subjective evaluation which may lead to biased results in some situations, therefore in addition we measured the evolution of the participants' center of gravity (COG) with the TechnoConcept balance board[2], as past literature showed postural sway to be a reliable feature to measure cybersickness (e.g., Ref. [4]). The embedded sensor can gather the postural sway signal in Forward/Backward and Left/Right directions and allows to compare the body's variance of COG before and after navigation in the VE.

3.3.3 Procedure

All the participants followed the same experimental procedure, starting with a clear and careful explanation, then a training session to the experiment with a basic description of VR knowledge. The whole procedure was designed as follows:

Table 1: Statistical results for the different measured items.

Item	Test	Statistical value	p-value	Sig.
Total time	H-test	17.468	.00003	**
Variation of area	ANOVA	4.573	.043	*
Total SSQ	ANOVA	5.638	.028	*
Nausea	ANOVA	5.876	.024	*
Oculomotor	ANOVA	5.882	.023	*
Disorientation	ANOVA	1.666	.210	
Efficiency	H-test	3.990	.046	*
Likability	ANOVA	4.330	.049	*
Accuracy	ANOVA	6.760	.016	*
Learnability	H-test	8.270	.004	**
Immersion	H-test	10.958	.00093	**
Naturality	H-test	1.381	.240	
Consistency	H-test	8.416	.004	**
Concentration	H-test	7.879	.005	**

1. Before being immersed in the VE, participants were requested to fill an SSQ (Q2) to check if they had already felt any cybersickness. The postural sway signal was also collected through the balance board with the intention of comparing the variance of the COG's area before and after the experiment.

2. The participants were assigned randomly one of the navigation method (joystick or semiautomatic) to travel in the VE and were requested to pick up all the coins.

3. After the participants finished the task, the total time for completing the task was recorded immediately. Again, they were asked to stand on the balance board in order to measure the variance of the COG's area after immersion in the VE. Then, Q2 and Q3 were filled at this stage.

4. On another day, the participants were invited to test the remaining navigation method following the same procedure as before.

4 RESULTS AND DISCUSSION

4.1 Statistical Tests

Since we did not collect an extremely large sample for the statistical analysis, we first validated the normality and homogeneity of the collected data with the Shapiro-Wilk test and the Levene test, respectively. Then, we performed a one-way ANOVA on data that were normally distributed and had equal variance. Otherwise, the Kruskal-Wallis H-test was used. The statistical value and the p-value for each measured item are summarized in Table 1, with a detailed description in the next subsection. The significance level was set to .05.

4.2 Results

Fig. 3 shows the difference between the two different travel interfaces in the VE in terms of the total time and the geometrical size of the COG's area. The COG's area was derived by projecting Forward/Backward (F/B) and Left/Right (L/R) postural sway signals onto the XY plane, then was defined as the optimum ellipse surrounding 90% of the sampled points as used for example in the work of Chardonnet et al. [4]. For each navigation method, the variation of the COG's area was considered to be an objective behavioral indicator and was measured as the difference before and after navigation in the VE. The joystick controller ($M = 303.83\,s$, $SD = 44.91\,s$) significantly required much more time to navigate in the VE compared to that of the semiautomatic technique ($M = 227.59\,s, SD = 16.83\,s$), while we can also see

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[2] http://www.technoconcept.fr/shop/index.php

that the COG's area significantly changed from ($M = 58.92\,mm^2$, $SD = 41.90\,mm^2$) to ($M = 27.63\,mm^2$, $SD = 42.55\,mm^2$).

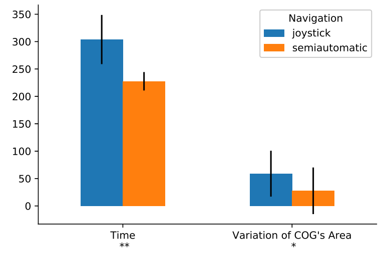

Figure 3: Comparison of objective indicators for both navigation techniques.

Fig. 4 depicts the results of the SSQ scores obtained from the questionnaires. The participants were requested to rate the amount of sickness they felt before and after each experiment. Among the three categories of the SSQ (nausea, oculomotor, disorientation), we found a significant decrease for the total SSQ score, nausea and oculomotor categories (34.13%, 41.63% and 40.00% respectively). The disorientation score decreased slightly of about 19.05%, but no significance was found.

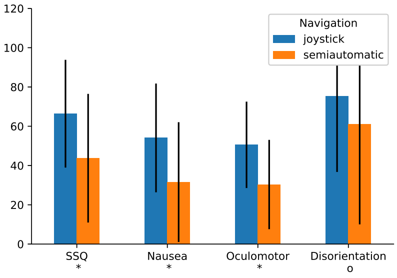

Figure 4: Comparison in terms of SSQ scores.

Fig. 5 shows the results from the participants after rating each navigation method in terms of efficiency, likability, accuracy, learnability, immersion, naturality, consistence and concentration based on a 5-point Likert scale (1=not at all, 5=extremely). The semiautomatic navigation technique significantly outperformed the joystick-based technique for all items except naturality. The joystick was reported to be easier to know how to use since the participants already experienced this kind of controller. However, there was no significant difference concerning naturality because navigation in the VE was still considered as different compared to navigation in the physical world as the participants reported after the experiment.

We also got a general feedback from the participants after the experiments. They liked the joystick's learnability more than with the semiautomatic technique, because they had already played or seen video games and could therefore control movements unconsciously; however, every time they wanted to move to one coin in the VE they had to constantly adjust their movements and therefore found it hard to locate themselves exactly. The experience with the joystick was also reported to be jerkier and less smooth during navigation. Concerning the semiautomatic navigation method, all the participants mentioned that they liked seeing the generated path as it could give them more motion cues about the moving direction, but some users also complained that they did not want to be constrained in the path and with pre-defined movements along the generated path.

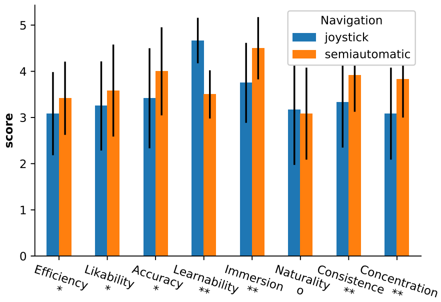

Figure 5: Comparison in terms of quality factors.

4.3 Discussion

Recall that we proposed two assumptions in order to show that the semiautomatic navigation technique could provide better user experience, and especially reduced cybersickness.

4.3.1 Validation of hypothesis 1

Semiautomatic navigation was much more efficient in comparison with the joystick method since the semiautomatic method generates optimized paths towards the desired position, and in this case, users can focus on the task instead of considering how to control navigation in the VE, which can be evidenced from the total time of task completing and also subjective evaluation shown in previous Sect. 4.2. With semiautomatic navigation, users only needed to set the target, then to follow the trajectory, and to use the gaze-directed method to make corrections if the path was not the preferred one. Participants seemed to appreciate the semiautomatic method considering all criteria except learnability because they were familiar with the joystick, which coincides to the previous study [18].

4.3.2 Validation of hypothesis 2

The significant decrease of the COG's area indicates that there was less sensory conflict in the semiautomatic navigation method, therefore the CNS could control the postural sway more easily as also reported in the work of Chardonnet et al. [3], which also confirms the sensory conflict theory. Other past studies also observed a similar conclusion that low sensory conflict normally induces less cybersickness [13]. However, the disorientation score did not witness any significant difference between the two different navigation methods, although the participants reported less disorientation when using the semiautomatic method. The reasons can be: a) the participants were requested to finish the task as fast as they could so they focused more on the task instead of looking around and exploring the VE, but concerning other items of the SSQ, semiautomatic navigation achieved better performance with the assistance of the motion planner which could get rid of unnecessary movements and involuntary visual stimuli. b) The sample size was not enough large since we had only 13 participants. Further studies with much more participants should be conducted.

5 CONCLUSION

Considering the sensory conflict theory, we designed a semiautomatic navigation method trying to reduce the generation of conflicted signals. We analyzed user experience in terms of cybersickness and other quality factors and we compared them with joystick-based navigation. Statistical analyses showed significant improvement in reducing cybersickness especially symptoms of nausea and oculomotor. This validates our hypotheses that when navigating using a joystick controller, users have to frequently change the speed and direction of movement and always look around for the target, consequently, leading to more sensory conflict. On the other hand, the motion planner in semiautomatic navigation may help users navigate in a VE with less unnecessary and jerky visual stimuli, therefore reduce cybersickness. In addition, semiautomatic navigation achieves better performance among several quality factors such as efficiency, likability, accuracy, immersion, consistency and concentration. Future work will focus more on user's intention and also the optimisation of navigation speed.

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