Virtual vs. Physical Navigation in VR: Study of Gaze and Body Segments Temporal Reorientation Behaviour

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Abstract

This paper investigates whether the body anticipation synergies in real environments (REs) are preserved during navigation in virtual environments (VEs). Experimental studies related to the control of human locomotion in REs during curved trajectories report a top-down reorientation strategy with the reorientation of the gaze anticipating the reorientation of head, the shoulders and finally the global body motion. This anticipation behavior provides a stable reference frame to the walker to control and reorient his/her body according to the future walking direction. To assess body anticipation during navigation in VEs, we conducted an experiment where participants, wearing a head-mounted display, performed a lemniscate trajectory in a virtual environment (VE) using five different navigation techniques, including walking, virtual steering (head, hand or torso steering) and passive navigation. For the purpose of this experiment, we designed a new control law based on the power-law relation between speed and curvature during human walking. Taken together our results showed a similar ordered top-down sequence of reorientation of the gaze, head and shoulders during curved trajectories between walking in REs and in VEs (for all the evaluated techniques). However, the anticipation mechanism was significantly higher for the walking condition compared to the others. The results presented in this paper pave the way to the better understanding of the underlying mechanisms of human navigation in VEs and to the design of navigation techniques more adapted to humans.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 Introduction

Being able to navigate in a Virtual Environment (VE) is a basic requirement for the majority of Virtual Reality (VR) applications. Over the last decades a wide number of navigation techniques have been proposed for this purpose [28], however, due to the limitations of existing VR systems (e.g. typical VR setups only enable to walk several meters), most of these navigation techniques do not require the user to perform real locomotion. Although a number of studies has focused on the impact of virtual navigation techniques in terms of performance, spatial awareness or even cybersickness, little is known about the impact of such techniques on the user behaviour. In this paper, we try to shed some light on how navigation techniques influence the visuo-locomotor coordination, and in particular the anticipation strategies between body segments like gaze, head and shoulders.

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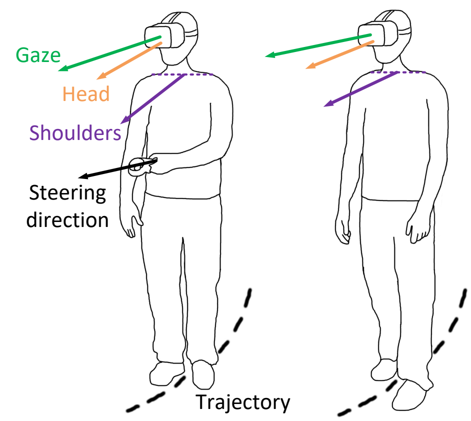

Figure 1: In our experiment, participants wore a head-mounted display and performed a lemniscate trajectory in a virtual environment. We investigated body segments (gaze, head and shoulders) anticipation synergies during navigation with five techniques including hand steering (left) and walking (right).

Human locomotion is a complex task involving motor and cognitive controls. Studies in the field of Neuroscience have shown the importance of the head to control locomotion, acting as an inertial platform and a frame of reference to help the coordination of body segments [33]. In particular, while performing a curved path in a Real Environment (RE), a top-down reorientation strategy is consistently observed [4, 11, 23]: the gaze anticipates the future direction of the movement, followed by the head and then the shoulders. However, this anticipation, which is common to all humans, can be affected by health issues challenging postural control and locomotion [27, 38].

These locomotion invariants have been mainly considered in REs, but there have been only few studies regarding the top-down hierarchy and gaze anticipation mechanisms during a navigation task [17, 37]. These works mainly assessed gaze and body segments behavior for 90° turns with passive or walking-in-place techniques.

In this paper, we evaluated how users perform a navigation task in VR according to different navigation techniques. We proposed for the first time to analyze gaze behavior and body segments orientation strategy during curved trajectories using several navigation techniques including walking, steering and passive techniques (Fig. 1). Our results enrich the understanding of human behavior in VEs and are discussed with respect to the design of new, human-centered navigation techniques which could improve users' experience.

In order to conduct this experiment, we designed a new control law for navigating in VEs based on the biomechanics of walking that provides similar navigation speed than physical walking in VE.

2 RELATED WORK

2.1 Navigation in Virtual Environments

Navigation is a basic interaction task in VEs that consists in controlling the virtual position of the user [28], involving two main subtasks: traveling, user's control of movement through the VE [8], and wayfinding, the ability of updating the self position and orientation relative to the known places in the environments and defining a path through it [14]. In this paper we only focus on the traveling component, and in particular its suitability to elicit behaviours that are observed during locomotion in REs. Thus, we will not focus on teleport-based or gesture based-techniques [7].

As such, walking is accepted to be the most ecological approach to navigate in a VE, as it better matches real locomotion tasks. However, the limited size of the physical workspace often prevent from using it in most of VR setups. Thus, since the beginning of VR systems, navigation techniques have been required in order to enable the user to navigate infinitely in disregard of the size of the physical workspace.

2.1.1 Physical VR Locomotion Techniques

In order to increase the navigation fidelity, a number of locomotion techniques involve physical body motion of the users. For example, redirected walking [35] is based on the imperfections of human perception concerning visual paths. While walking, users can be imperceptibly reoriented using visual manipulations of the VE so that they can follow a straight trajectory in the VE while performing a curvilinear trajectory in the RE. Another approach is to consider the manipulation of the VE instead of manipulating user's viewpoint. Suma et al. introduced change blindness that redirects users through a dynamic evolution of the VE [43]. While the user is focusing on a specific task, the VE can be altered (e.g. rotation of a doorway or realignment of a corridor) without the user noticing it. Other techniques are based on users steps without performing physical translations, such as walking-in-place (WIP) [41, 44] that allows users to navigate in a VE by alternating small steps while remaining in a static position. Finally, there also exists hardware solutions using omni-directional treadmills [13] or low-friction surfaces [24]. They provide walking sensations through proprioceptive feedback and can be used in small workspaces. However, all techniques mentioned still present a number of challenges that make them difficult to spread. Redirected walking techniques still require a moderately large working space and can be challenging to define the right thresholds of rotations and translations to subtlety reorient users [42]. WIP can decrease the feeling of presence and sacrifices equilibrioception [46], and hardware-based solutions are either too expensive, cumbersome or complex to master for being embedded in VR applications.

2.1.2 Virtual VR Locomotion Techniques

In contrast, a number of locomotion techniques that do not require any physical motion from the user have been proposed. As such, steering techniques [6] are by far the most employed ones in most VR applications and only require small workspace. Steering techniques, are mainly characterized by how the user provides the navigation direction and the navigation speed [28]. The navigation direction is typically provided by a user's body segment such as the head, the hand or the torso, and defined by pointing or looking towards the desired direction. Then, the navigation speed is determined by a control law that determines the navigation speed depending on the user's inputs (discrete, e.g. a button press or continuous, e.g. a joystick). Yet, most VR applications use simple control laws such as constant or linear mappings in order to reach a comfort speed. In a human scale environments, a navigation speed between 1m/s and 1.4m/s is typically considered [31]. However, steering techniques rarely take into account the actual trajectory of the user. One of the rare examples of such, is the control law used by the Joyman [31] that modulates the tangential speed according to the actual rotational speed, in order to better resemble the dynamics of real walking. Finally, fully automated techniques can also be employed in situations where users inputs are limited or to constraint users navigation. However, steering and automatic techniques do not provide proprioceptive or vestibular information of walking and therefore generate a poor sensation of locomotion, that can result in a decreased spatial awareness [10] and the potential increase of motion sickness [40].

2.2 Visual control of human locomotion

2.2.1 Visual information

The human visual system plays a major role while navigating in REs since it gathers information about the characteristics of our surrounding environment, about our position and about our relative motion with respect to the other the elements in the environment. From the ecological theory perspective [25], one can describe an environment-agent system, with a strong coupling between perception and action, namely the perception-action loop. Gibson developed the theory of direct perception where the visual stimulus is rich enough to specify the action an agent can perform within the observed environment. Note that while in a RE observers can perceive the environment with their own perceptual system and act with their musculoskeletal system, the perception action loop is modified in VR since observers perceive the VE through displays (screen, HMD, ...) and act frequently using interfaces coupled with control laws as described in the previous section.

Visually guided locomotion has received considerable attention in the past [16, 30, 32, 48]. For example, two main strategies to move towards a goal have been identified. The first one, proposed by Gibson [16], leverages the optical flow created by the apparent motion of each point composing the sequence of images perceived by the walker during his motion. Steering toward a goal is then achieved by superposing the focus of expansion of the flow with the target to reach. The second strategy, proposed by Rushton [39], aims at aligning the locomotor axis with the perceived egocentric direction of the target to reach. Studies have shown that both strategies are used during locomotion steering [49], with a different predominance depending on the amount of available visual information [39, 45]. In the context of a collision avoidance task, other invariants from the optical flow can be used such as the bearing angle [12], i.e. the angle between the walker's gaze (directed towards the obstacle) and the walker's heading that specifies whether a collision will occur, or tau [29], i.e. the inverse of the dilatation rate of the angle formed by an approaching object on the observer's retina, which specifies when the collision will occur (i.e., time to contact).

2.2.2 Gaze and body segments behaviour in REs and VEs

In REs, studies considered the gaze behaviour in relation with body segment synergies. There exists a hierarchical "top-down" control during walking. Indeed, when walkers perform a curved trajectory, their head anticipate the future direction, meaning that head orientation is not tangent to the locomotor path but always oriented towards the future direction. This locomotor invariant has been observed with different experimental conditions: trajectories at 90° [18], but also trajectories at 30° and 60° [23]; walking forward or backward [18]; with or without vision [11]; using different walking speeds [34]. No matter what the experimental conditions are, the head always anticipates the future direction. Researches showed that the head anticipates 200ms before the body [4,18]. Moreover, some studies showed that head anticipation depends on the trajectory curvature [4, 20]. Finally, this head anticipation behavior was reinforced thanks to a study where they immobilized the head to the trunk. Results showed that the trunk reorients itself faster to align the head towards the future direction [22].

In VEs, few works have investigated gaze and body segments behavior during navigation task. For instance, in a VE where the motion was simulated at different speeds, Grasso et al. found that during 90° turns the head turns at a constant distance instead of a constant time [17]. Reed-Jones et al. studied the effects of constraining eye movements during a 90° turn in a VE while walking in place [36]. They found a significant difference in temporal and spatial coordination of body segments between free gaze and fixed gaze navigation. In free gaze condition, the top-down reorientation strategy is similar than in walking in RE (eyes then head, trunk and pelvis) whereas in fixed gaze condition the body segments moved in unison ("en-bloc"). These results point out that eye movements trigger the coordination of the whole-body reorientation in 90° turns. However, these studies didn't assess gaze and body segments behavior for curved trajectories with different navigation techniques.

A lot of new navigation techniques or control laws have been designed but these work haven't considered enough how navigation techniques could influence the body segments coordination. Taking into account knowledge from the visual control of human locomotion to contribute about the understanding of human behavior in VEs could help to improve navigation in VEs.

3 User Study

The goal of this study was to investigate the temporal synergies between body segments (gaze, head and shoulders) during a navigation task along a curved trajectory. While a wide number of navigation techniques could have been analyzed, this study assessed five navigation techniques that are widely employed in VR systems and also provide different degree of user control. In particular, we focused on real walking, three virtual steering techniques and one passive navigation technique. Our main hypothesis was that navigation techniques with higher fidelity to real walking would lead to synergies between body segments closer to the ones observed during real locomotion tasks. This experience was strongly inspired from paradigms already used to assess gaze anticipation during curved trajectories in RE [2,4].

3.1 Participants

20 participants (15 males and 5 females) aged between 19 and 29 years old (23.5±2.33, mean±SD) without any ocular or locomotion disorders volunteered to this study. They all have already experienced VR once (33% regularly, 66% few times) and videos games (70% regularly, 30% few times). They were naive to the purpose of the experiment and signed an informed consent form. The study was approved by the Inria Ethics Committee (reference: 2018-008/02) and conformed with the standard of the declaration of Helsinki.

3.2 Apparatus

Users were immersed in the VE using the FOVE HMD that includes an eye-tracker. The display Field of View (FoV) was 90° (horizontal). We used three HTC Vive trackers and two HTC Vive base stations to track users' head and shoulders positions. Users wore a MSI VR One 7RE backpack, including a GTX 1070 GDDR5 and 16Gb RAM (Fig. 2). We paid particular attention to the HMD cables to prevent users from being bothered by them, as it could potentially influence users behavior.

The VE (Fig. 2) was a 8x8x4 meters rectangular parallelepipoid. We added a noise texture to the walls so that rotations generate motion flow but without any salient features. We designed a bigger VE than the workspace (which was 4x4 meters) in order to preserve users' personal space. Indeed, there exists a "collision envelop" which defines the comfortable distance between a user and an obstacle. This distance would depend on the internal perception for safe navigation. This was confirmed in our pilot studies where we noticed that coming close to a wall in the VE disturbed the users during the navigation task.

In order to study body reorientation strategies during navigation, we defined the trajectory to perform as a Gerono lemniscate defined by the parametric Equation 1. This standardized trajectory has been already used in studies about human locomotion in REs [2,4].

$$\begin{cases} x(t) = \cos(t) \\ y(t) = \sin(t) * \cos(t) \end{cases} \tag{1}$$

The center of the VE was represented by a black cross, which also corresponded to the center of symmetry of the trajectory displayed in blue on the ground. Two cones were arranged in the VE to delimit the trajectory (placed two meters on either side of the center). Besides, an arrow indicated in which direction the user had to perform the trajectory (either from the left or from the right as shown in Fig. 2). Some feedback text was displayed in front of users' initial position wall to provide them information during the experiment. All visual information were hidden when users performed the trajectory, only the walls and the floor were displayed during the task.

3.3 Control law based on the biomechanics of walking

In the experiment, participants had to perform lemniscate trajectories. During the pilot experiment we observed that most common control laws for virtual steering were not appropriate for the given task. Due to the coupling between speed and curvature during human locomotion, constant speed methods resulted in unrealistic speed profiles and user-controlled methods were difficult to master. Although the control law described in [31] could have been used, it was designed for a joystick-based input. Thus, we designed a new control law based on the biomechanics of human walking that uses the relationship between speed and curvature [21, 47]. During a continuous trajectory, the instantaneous speed varies according to the local radius of the curvature (see Equation 2) as a power law:

$$R(t) = \frac{(\dot{x}^2 + \dot{y}^2)^{\frac{3}{2}}}{\dot{x}.\ddot{y} - \ddot{x}.\dot{y}} \tag{2}$$

where $\dot{x}$, $\dot{y}$, $\ddot{x}$ and $\ddot{y}$ are respectively the first and second derivatives of x and y coordinates of the user's position in the environment. In the case of walking trajectories, the speed of locomotion is proportional to the cubic root of the radius of curvature [21,47] (Equation 3):

$$S(t) = K.R(t)^{\frac{1}{3}} \tag{3}$$

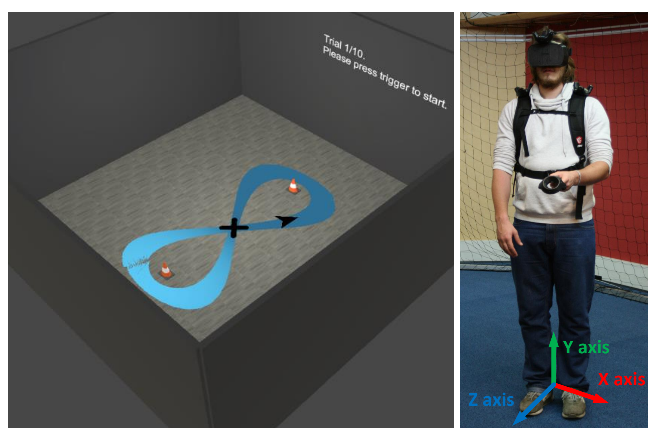

Figure 2: Left - The VE used for the experiment. The roof was removed for illustration purpose. Right - Participant equipped with the FOVE HMD, a backpack, the HTC Vive trackers and the HTC Vive controller. The trackers were used to track the user's head and shoulders.

where $S(t)$ is the horizontal speed at time t, K is a gain speed coefficient and $R(t)$ is the radius of local curvature of the trajectory at time t. The coefficient K was empirically determined during pilot tests in which users walked along the lemniscate trajectory while wearing a HMD. We analyzed the mean velocity profiles and we chose the coefficient $K = 0.5$ so that the control law would have similar speed profiles than walking in VEs.

Given this power-law relation, our control law updates the speed and position of the user in the VE at every frame only if the user pressed the trigger button of the hand-held controller as follows:

1. The user speed $S(t)$ was updated according to the 1/3 power law (Equation 3) taking into account the local curvature (Equation 2) of the trajectory.

2. The user position $P(t)$ was updated using Equation 4. The normalized vector $\vec{d}$ is defined by the orthogonal projection of the direction of a user's body segment (head, hand or torso) on the XZ plane (i.e. the floor).

$$P_n(t) = P_{n-1} + (\vec{d} * S(t) * \Delta t) \qquad (4)$$

Finally, since the power law can only be applied to curved trajectories (in a straight line the radius of curvature is infinite), we first defined a maximum navigation speed of 1.4m/s, which is considered as a comfortable walking speed in REs [5]. However, during the pilot study we observed that, when physically walking in VR, users rarely achieved the speed of 1.4m/s. Therefore in order to ensure that real and virtual navigation achieved similar navigation speeds, we decided to set the maximum navigation speed to 1m/s that better corresponds to walking speeds observed in VR [15]. Sudden accelerations and decelerations were filtered to avoid abrupt changes in the perceived speed.

3.4 Experimental design

We used a repeated-measures design in which the independent variable was the navigation technique. We considered 5 navigation techniques: (1) **Walking** - 1:1 mapping between the VE and the RE. Users walk in the VE as they walk in the RE. (2) **Torso Steering** - Users navigate by pressing Vive controller trigger. It uses torso direction to specify the direction of travel. Motion speed is defined by the control law described previously. (3) **Hand Steering** - Similar to Torso steering except that the hand defines the direction of travel. (4) **Head Steering** - Similar to Torso steering except that the head defines the direction of travel. (5) **Passive** - The virtual camera followed a path defined as a Gerono lemniscate (Equation 1) and the speed of the motion was automatically updated using the control law described before.

The hypotheses guiding our study were: **[H1]** Users perform the trajectory in similar manner with the different navigation techniques. **[H2]** Gaze anticipation is preserved during navigation in VE for the walking condition. **[H3]** Top-down reorientation strategies differ depending on the navigation technique.

3.5 Experimental Protocol

First, participants read and signed the consent form which provided detailed information regarding the experiment. The experiment was divided in five blocks, one for each navigation technique. For each block, participants filled first the Simulator Sickness Questionnaire (SSQ) [26] and then they were equipped with the HTC Vive trackers and the backpack, placed at the center of the physical workspace and then equipped with the HMD. For each block, the eye-tracking was calibrated and then participants performed 10 repetitions (where the first two trials were considered as training trials) as follows:

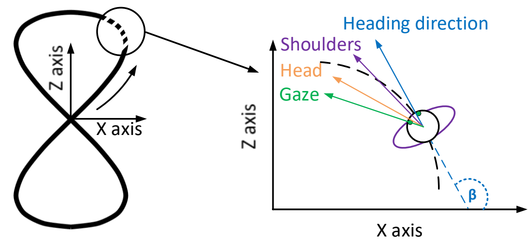

Figure 3: Left - Participants had to perform a eight-shape trajectory in the VE by memorizing it (we displayed any visual information on the floor). Right - Orientation of body segments and heading direction in the horizontal plane. Horizontal angles for each body segments and β for heading are defined as the unwrap tangent function of the ratio X/Z, where X and Z represent positions of the body segment.

1. The coordinate system of the FOVE and the HTC Vive trackers were first aligned in order to avoid any potential orientation mismatch. The calibration procedure required participants to align their head direction with a virtual red sphere. Once the participant was aligned with the sphere, the two coordinate systems were aligned. This procedure ensured that the alignment error was lower than 1 degree.

2. After the calibration, participants could see the lemniscate trajectory drawn on the floor, a black cross representing the origin of the trajectory, a black arrow indicating their starting orientation and a text informing the trial number and the sentence "Please press the trigger to start".

3. Once participants were placed on the black cross and aligned with the black arrow, they could press the controller trigger that started a 3 seconds countdown. When the countdown was over, all the visual information regarding the trajectory were hidden and they could start the task.

4. Participants performed the trajectory using the current navigation technique. The start and end points of the trajectory were the same. The trajectory was validated using an invisible checkpoint system which ensured that users performed a valid trajectory. In case of an invalid trajectory, the trial was not recorded and participants had to perform it again.

After each block, the users took off the VR equipment then filled a SSQ questionnaire to monitor their cybersickness and a NASA Task Load Index (NASA-TLX) form [19] to assess mental demand, performance, effort and frustration. Between blocks, participants had a 5 minutes break to minimize potential negative effects of cybersickness. To minimize learning effects, the order of the conditions was counterbalanced using a Latin-square design. In total the experiment duration was one hour. At any time, users could ask for a break or stop the experiment. Yet, this never happened.

3.6 Data measurement

Along the entire experiment we ensured the maximum frame rate of the FOVE which was 70Hz. We measured the position and orientation of the head and shoulders using the 3 HTC Vive trackers. The reference coordinate system was defined by the HTC Vive tracking system as shown in Fig. 2. Eye-Gaze orientation was measured thanks to the two integrated infrared eye-trackers in the FOVE HMD which had an error of less than 1°. We also measured the time to perform the trajectory and the distance achieved in the VE and the RE. Regarding the subjective measurements, we measured the changes on the SSQ scores for each condition, the physical and mental effort using the NASA-TLX questionnaire and the users' subjective feedback for each condition.

Table 1: Mean and standard deviation for time execution, distance achieved in VE and RE, average speed and curvature for each condition.

	Walking	Torso Steering	Hand Steering	Head Steering	Passive
Average speed (m/s)	0.83 ± 0.11	0.83 ± 0.04	0.85 ± 0.05	0.84 ± 0.06	0.88 ± 0.02
Average curvature (1/m)	0.044 ± 0.015	0.036 ± 0.017	0.037 ± 0.016	0.034 ± 0.022	0.035 ± 0.018
Dist in VE (m)	14.63 ± 1.14	12.83 ± 1.40	13.35 ± 1.62	12.40 ± 1.85	11.56 ± 0.23
Dist in RE (m)	-	2.36 ± 0.44	2.16 ± 0.49	2.43 ± 0.50	2.17 ± 0.30
Time (sec)	18.0 ± 2.74	15.34 ± 1.20	15.7 ± 1.54	14.64 ± 1.52	13.18 ± 0.15

3.7 Data analysis

To analyze the temporal sequences between the body segments, we resampled them at a frequency of 30 Hz as done in previous work [4], then data were filtered with a butterworth low-pass filter with a cutoff frequency of 1 Hz to remove oscillations due to stepping activity [2].

Participants' trajectory was computed as the displacement of the shoulders barycenter. After assessing that the trajectory direction did not have any effect on the results, we mirrored the trajectories to the right. We then computed participants' speed as the first time derivative of their position as well as the instantaneous curvature of the trajectory (Equation 2).

To study body segments orientation behavior, we computed horizontal angles (in degrees) for each body segment (gaze, head, left shoulder and right shoulder) and the heading direction as the unwrap arc-tangent function of the ratio X/Z, where X and Z were the coordinates of the vector that defined the orientation of each body segment in the horizontal XZ plane (Fig. 3). To study temporal synergies, the relative time delay of each body segment was computed by cross correlations of their horizontal orientation in space.

In total, we collected 1 000 trajectories (20 users, 5 conditions and 10 trials per condition) during the experiment. We removed first and second trials from each condition for the analysis because they were considered as practice trials. Among the 800 remaining trajectories, we noticed that 28 trajectories (3.5%) were invalid: sometimes participants performed correctly the whole trajectory except at the end where they were not able to go back to the center of the VE and they had to make half turn to end the trial. We therefore removed them from the analysis.

For each dependent variable, we first checked their normal distribution with the Shapiro-Wilk test. Then we did an analysis of variance (ANOVA) with repeated measures to assess the effect of the condition (walking, torso steering, head steering, hand steering and passive). We considered the threshold $p < 0.05$ as significant. We used pairwise t-tests with Bonferonni corrections for the post-hoc analysis when necessary. If the distribution of the dependent variable was not normal, we used the Friedman ANOVA test and post-hoc pairwise Wilcoxon tests with Bonferroni corrections.

3.8 Results

3.8.1 Trajectory execution

All the participants performed correctly the trajectories during the experiment according to our requirements. Table 1 reports the characteristics of the trajectories performed by participants and Fig. 4 shows the average trajectories achieved by each participant per conditions. Friedman test showed that the navigation technique affected average speed ($\chi^2(4) = 17.72$, $p < 0.01$) as well as average curvature ($\chi^2(4) = 11.6$, $p < 0.05$). Pairwise post-hoc comparisons showed that the speed was lower for Torso Steering than for Passive ($p < 0.01$) and that the curvature was lower for Head Steering than for Walking ($p < 0.05$). Even if some difference exists, the absolute difference is low and the trajectories remain similar for each condition in terms of average speed and curvature (see Table 1).

Friedman test showed an effect of the navigation technique on the distance achieved in the VE ($\chi^2(4) = 39.8$, $p < 0.001$). Post-hoc tests showed that the smallest travelled distance in VE was observed with passive navigation (11.56m $\pm$ 0.23, $p < 0.05$) and the highest with walking (14.63m $\pm$ 1.14, $p < 0.05$). Distance travelled in the RE during steering or passive conditions were 5 times smaller than the one in VE. All users used at maximum 1m^2 working space to navigate with steering and passive conditions. Friedman test showed an effect of the navigation technique on the distance achieved in RE ($\chi^2(4) = 10.68$, $p < 0.05$) but post-hoc analysis did not reveal any significant differences. The task completion time was affected by the navigation technique ($\chi^2(4) = 56.8$, $p < 0.001$), pairwise comparisons showed that passive was the fastest (13.18 $\pm$ 0.15, $p < 0.001$) and walking the slowest (18.0 $\pm$ 2.74, $p < 0.01$).

3.8.2 Temporal anticipation of body segments

Fig. 5 shows typical temporal sequences of body segments (gaze, head, shoulders) and heading horizontal turning angle during a trial for each condition. The evolution of these angles differed between conditions. In walking and torso steering, there was a coupling between the heading and the shoulders (i.e. both curves are overlapped on the figure) whereas the coupling for hand steering and head steering was between the heading and the head. Passive condition showed no particular coupling between the body segments.

The left chart on Fig. 6 shows the average temporal anticipation, from gaze and head with respect to the heading direction. During walking, there was an anticipation of gaze (529.23 ms), which precedes the anticipation of the head (204.58 ms) with respect to the heading direction. One way repeated measures ANOVA showed an effect of the condition on gaze anticipation with respect to the heading direction ($F_{3.42,64.98} = 29.47$, $p < 0.001$, $\eta_p^2 = 0.61$) and post-hoc analysis indicated that the anticipation was faster during walking than every other conditions ($p < 0.001$), except for torso steering where the effect was not significant ($p = 0.059$). Temporal anticipation of the head with respect to the heading direction was also affected by the condition ($\chi^2(4) = 50.744$, $p < 0.001$). Post-hoc analysis indicated that head anticipation was faster during walking than for the other conditions ($p < 0.001$), except for torso steering where the effect was not significant ($p = 0.12$).

We also investigated the temporal anticipation between body segments horizontal angle (Fig. 6 right). For the walking condition, there exists a gaze anticipation with respect to the head (167.40 $\pm$ 78.2 ms) and the shoulders (639.10 $\pm$ 182.11 ms). Temporal anticipation from gaze to head is affected by the condition ($F_{3.16,60.08} = 2.97$, $p < 0.05$, $\eta_p^2 = 0.14$). Pairwise tests showed a faster gaze anticipation related to the head for hand steering than passive ($p < 0.05$). There was also an effect of the condition on the temporal anticipation from head to shoulders ($F_{3.10,58.89} = 20.46$, $p < 0.001$, $\eta_p^2 = 0.52$). This anticipation was significantly faster for walking than all the other conditions ($p < 0.001$). Finally, the condition also affected the temporal anticipation from gaze to shoulders ($F_{3.48,66.16} = 19.81$, $p < 0.001$, $\eta_p^2 = 0.51$) with again a faster anticipation for walking than all the other conditions ($p < 0.001$).

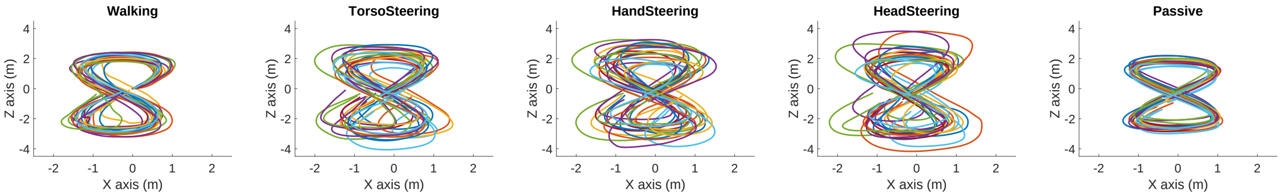

Figure 4: Average trajectories achieved by each participant for all conditions.

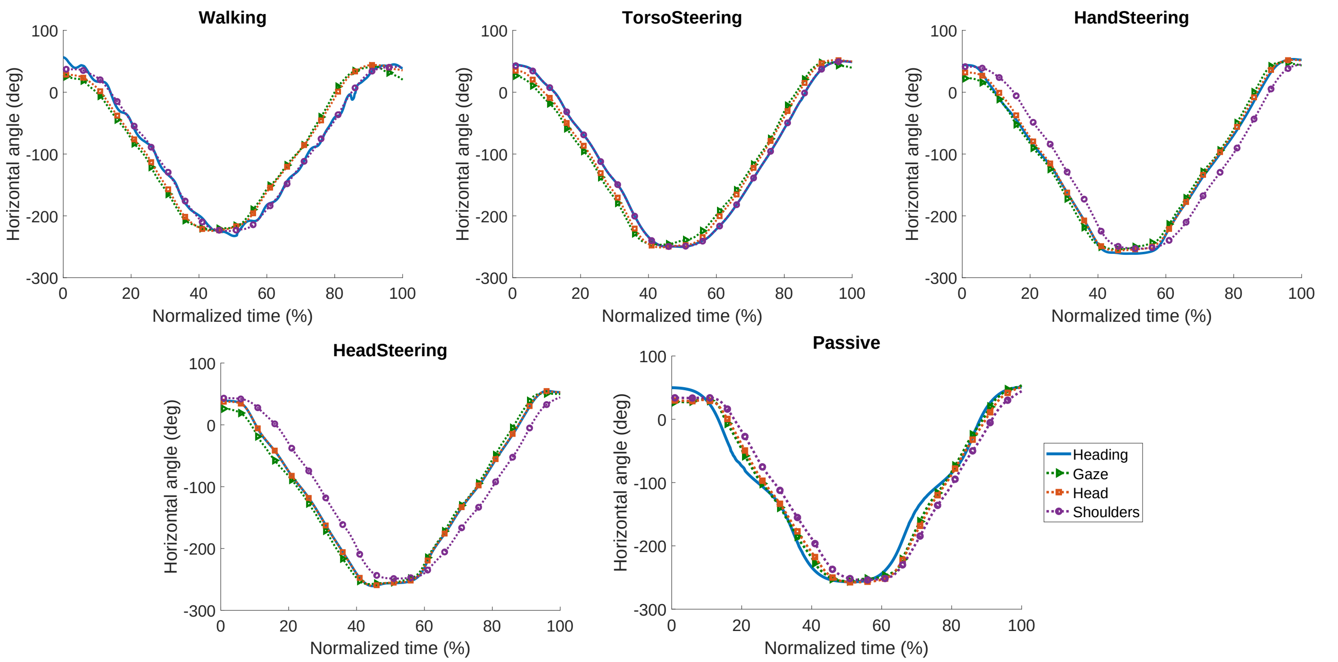

Figure 5: Typical evolution of the average angle of gaze (green), head (orange), shoulders (violet) and heading (blue) while performing the trajectory per condition. For the walking and torso steering conditions, we can notice the coupling between the heading and the shoulders angles (both curves are overlapped) whereas for hand steering and head steering, the coupling is between the heading and the head angles. Passive condition shows no particular coupling between horizontal angle of body segments. A body segment anticipation can be noticed if the evolution of its horizontal angle is shifted to the left wrt. the heading angle evolution.

3.8.3 Subjective questionnaires

In general, participants did not experience any simulator sickness symptoms during the experiment, which was confirmed by the SSQ scores. Moreover, the navigation techniques had no effect on the SSQ scores ($\chi^2(4) = 3.9375$, $p = 0.41$) as well as on nausea ($\chi^2(4) = 3.64$, $p = 0.45$), oculomotor ($\chi^2(4) = 7.33$, $p = 0.11$) and disorientation ($\chi^2(4) = 5.1839$, $p = 0.27$) subscales. The TLX-NASA subscales were not significantly affected by the technique expect for the physical demand ($\chi^2(4) = 31.471$, $p < 0.001$) where users indicated that walking was more exhausting than the passive navigation ($p < 0.05$). We finally asked users to sort each technique from the most preferred to the least preferred. Walking was globally the most preferred, with half of the participants who ranked it first, followed by the steering techniques, with a higher preference for head and torso than hand steering. Passive was the least preferred with 12 participants who ranked it last.

4 Discussion

Our study focused how user behavior was affected by the navigation technique. In particular, we investigated gaze and body segments anticipation as well as the orientation strategies across several navigation techniques (walking, torso/hand/head steering and passive). Our main objective was to assess whether gaze anticipation, previously shown during curved trajectories while walking in REs, still exists in VEs and whether there is an influence of the navigation technique used. By combining knowledge from biomechanics and computer science, we designed an experiment where participants had to perform a lemniscate shape using 5 different navigation techniques. We analyzed the trajectories performed by participants as well as their gaze and body segment temporal reorientation behaviours. On overall, regardless of the navigation technique considered, our results show that participants performed similar trajectories and that they had a top-down reorientation strategy to perform curved trajectories in VR.

4.1 Stereotypy of trajectories is preserved in VE

Goal-directed locomotion in REs can be characterized as a stereotypic task [20]: for a given initial and final position and orientation, it was shown that walkers perform this task in a very similar manner, either considering intra and inter individual variability of the trajectory. This property was also demonstrated in VEs using several locomotion interfaces [9], suggesting common principles that govern the control of the trajectory. Our study, even using a new control law, leads to the same conclusions across all the tested navigation techniques. Trajectories had qualitatively very similar shapes (Fig. 4) and very small differences were observed in term of their kinematics.

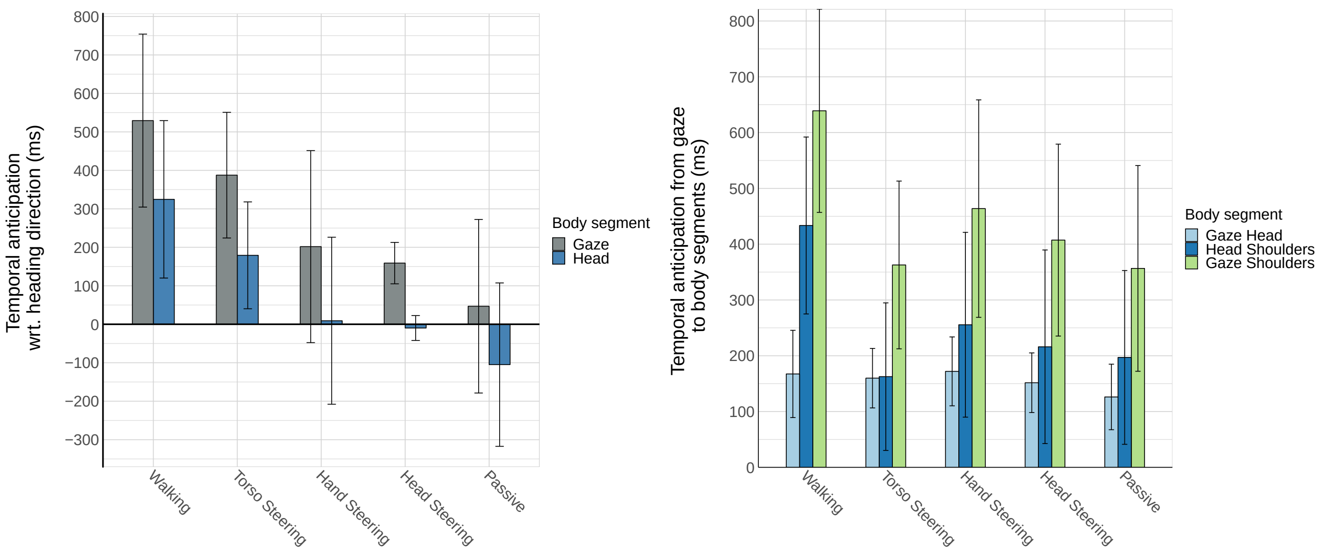

Figure 6: Left - Mean and standard deviation of temporal anticipation (in ms) of gaze and head horizontal angles wrt. the heading direction; Right - Temporal anticipation (in ms) from gaze to head and shoulders horizontal angles for each condition. A positive value means an anticipation of the first body segment on the second one whereas a negative value means an anticipation of the first body segment on the second one.

This confirmed our first hypothesis **[H1]**. This is important for a fair comparison of the body segments temporal orientation delays since it was previously shown that the reorientation behaviour is influenced by the path followed [4].

We can however notice a larger variability across participants when considering steering techniques with respect to walking. This may be explained by a higher difficulty of navigating with such techniques that provide less sensory information about motion perception. We can also discuss our VE which was minimalist to avoid any influence on the gaze behaviour but the lack of salience points may have led to poor optic flow information. Let's note that in these steering conditions, few users were performing a eight-shape trajectory in the RE as well.

For the purpose of our experimental task, we designed a new control law based on the relation between velocity and curvature during human locomotion. This law was relevant since velocity profiles as well as the geometry of the path performed were similar between physical walking and the other techniques. This motivates the use of the knowledge from biomechanics and neuroscience to design new navigation control laws. Future work is needed to evaluate whether such control laws could provide better users' experience and comfort in VEs.

4.2 Gaze anticipation during walking in VE vs. RE

Our experiment was based on previous studies that assessed gaze anticipation behavior during a curved locomotor trajectory in a RE [2, 4, 11, 18, 23]. As these previous works, we were able to demonstrate that gaze also anticipates body reorientation when physically walking in VR with an HMD, that confirmed our second hypothesis **[H2]**. For a deeper comparison, Table 2 shows a summary of our results with respect to the literature in RE. Our results for the walking condition in VE had similar order of magnitude than previous works in RE but the delays were higher suggesting that gaze anticipates more the change in heading in VEs than in REs. We hypothesize that higher anticipation could be explained by several reasons: (1) a shorter field of view which requires higher anticipation in order to perform the trajectory. Authié et al. showed that the gaze behavior of people with a shorter FoV (affected by retinitis pigmentosa) have larger head movements (a wider horizontal exploration of the environment) during curved trajectories than the control condition [3]. A shorter FoV may impact the gaze activity but additional work is needed to assess the impact of FoV in body segments behavior. (2) a "safety" mechanism which forces the user to anticipate more in a VE because participants cannot see their body while walking in the RE. (3) the impact of HMD and trackers weight on participants' head which could modify delays. To investigate these factors, further studies are required.

4.3 Reorientation strategies and navigation techniques

Our results showed that navigation techniques had an effect on temporal anticipation when considering both heading direction (gaze-heading and head-heading) and body segments (gaze-head, head-shoulders and gaze-shoulders), which confirms our third hypothesis **[H3]**. Especially, walking in VE induces significantly larger delays than steering and passive techniques. However, unlikely walking in VE, head-shoulders and gaze-shoulders delays for steering techniques are closer than Bernardin et al. delays for walking in RE [4].

Torso Steering: Gaze heading and head heading delays were different between torso steering compared to the other steering techniques. Moreover, torso steering had the closest behavior about gaze anticipation than walking in RE. One reason could be that steering direction provided by the torso would be more natural and participants would anticipate more easily thanks to the decoupling between head direction and heading direction which allows the head not being involved in the steering direction. This hypothesis is discussed in Arechavaleta et al. work in which they showed that human locomotion can be approximated by a nonholonomic system [1]. They compared different body reference frames (head, shoulders and pelvis) and their results showed that shoulders can be compared as a steering wheel that steers the human body with a delay of around 200ms. It means that shoulders' trajectory is less affected by oscillations induced by step alternation. Among the 20 participants, we identified 5 of them where the head shoulders temporal delay was smaller than 50ms. It means that these participants were reorienting the head and shoulders almost simultaneously, resulting to a "en-bloc" reorientation strategy. This behavior has been noticed in RE as well and can be affected by some diseases challenging postural control and locomotion. For instance, in patients with stroke, Lamontagne and Fung [27] showed changes in the reorientation strategies modifying the amplitude and the timing of the anticipation.

Table 2: Mean and standard deviations of the temporal anticipation (in ms) of gaze and head with respect to the heading direction in VE and RE and gaze related to body segments. Our results refer to walking in VE whereas [2, 4] refer to walking in RE.

	Gaze Heading	Head Heading	Gaze Head	Head Shoulders	Head Shoulders
Our results	529.23 ± 224.76	324.65 ± 204.56	167.40 ± 78.20	433.49 ± 158.54	639.10 ± 182.11
Bernardin et al. [4]	404.45	182.49	202.66 ± 83.08	212.63 ± 161.99	443.51 ± 202.92
Authié et al. [2]	400 ± 50	200 ± 10	-	-	-

Besides, another study showed that physical deficiency like a rupture of the anterior cruciate ligament has an impact in the timing of body segments reorientation [38]. Injured participants used a different reorientation strategy where the head anticipated less the trajectory. "En-bloc" strategies would then allow a decrease of the degrees of freedom to control when turning.

Hand Steering: Since torso and head are involved in the reorientation strategy during curved trajectories, we were wondering which would be the users' strategy when the steering control is initiated by the hand. From the 5 participants that had a temporal anticipation between head and shoulders smaller than 50ms with torso steering, 4 of them also had head shoulders delay smaller than 50ms with hand steering. These participants had a different strategy: they were putting the controller perpendicular to their torso and simultaneously turned the controller and their torso, which resulted to a "en-bloc" reorientation strategy with a lower head shoulders temporal anticipation. For the others, the controller was not aligned to the trunk and they rotated their wrist to steer, which created a dissociation between the body segments reorientation and the steering direction, and therefore higher head shoulders delays.

Head Steering: This technique is used oftenly in VR applications since it is easy to develop and intuitive for the user. Regarding the temporal anticipation the head cannot anticipate the trajectory (delay head heading close to 0ms) and the gaze heading delay was lower than in walking and torso steering. However, users with "en-bloc" strategy for hand and torso steering had a normal anticipation synergy with this technique. We can wonder if head steering should be chosen rather than torso steering which is less used, but allows anticipation of the head with respect to the future trajectory by preserving same kinematics properties.

Passive: Regarding temporal anticipation with respect to heading direction, the variability between users suggest that the reorientation strategy could differ. Some of them would anticipate the future trajectory whereas others would reorient their body later. That was especially the case for passive navigation where participants did not have any control about the virtual trajectory, meaning that they had to figure out when the turns would occur.

We noticed a difference for gaze head delays only between hand steering, where gaze anticipates faster related to the head, and the passive condition. It means that gaze temporal anticipation related to the head remains rather consistent during the navigation but the coupling head-shoulders differs according to the navigation technique as described before. From the perspective of designing navigation techniques based on the synergies of body segment orientations, this result suggests that gaze-based steering might not be necessary as the head orientation closely follows the gaze orientation.

We investigated the relation between the delays and the users' preferences. We could have expected that the closer the delays are to walking in RE, the more users prefer the navigation technique. However, temporal anticipation from gaze to head and shoulders were similar between steering techniques, and head steering (which is the second most preferred) had the shortest delays with respect to heading after passive navigation (which is the least preferred technique). Although we identified different behaviors according to the navigation technique, we did not notice any correlation between anticipation and cybersickness.

5 Limitations and Future Work

Through this user study, our aim was to contribute to the understanding of human behaviour in VE. We were interested in how users would reorganize their body segments orientation during a navigation task involving a curved trajectory (leminscate) in a sober VE (without salient objects in order to minimize the optical flow). Our experiment was performed in a simple environment to avoid any influence on the gaze behaviour (i.e., some elements can attract the gaze) and to allow the comparison with real world experiments [2,4]. However, such an environment is not common in most of VR applications. Thus, future works will have to consider more ecological situations, such as a free trajectory in richer and more complex environments. This would allow to evaluate whether this anticipation strategy still apply in more realistic VR conditions.

The presented experiment did not assess how users would perform the virtual task in a real environment. We decided not to include the real task as, considering that the FoV could have a potential impact on reorientation behaviour [3], it would have required to restrict the users' FoV in the real condition in order to match the FoV of the HMD. Additional studies should be conducted in order to better establish the role of the FoV in VE and RE, and determine up to which degree the FoV could have influenced the results.

Regarding the eight-shape trajectory, a new control law was designed (Sect. 3.3) based on the velocity-curvature relation observed in real locomotion tasks. In overall the trajectories performed by participants followed a similar pattern as compared to the real walking condition but further work is required to better evaluate this control law, in comparison with other ones and in a more natural setup.

Finally, it would be interesting to evaluate the anticipation behaviour with other techniques widely used in VR applications such as WIP or redirection walking techniques.

6 Conclusion

In this paper, we described an experiment that evaluated gaze and body segments behavior while navigating along an eight-shaped trajectory. The experiment considered five navigation techniques exhibiting different levels of fidelity and control. First, compared to real world locomotion behaviours [2, 4], the results confirmed that a temporal top-down reorientation strategy was preserved while walking in the VE but also for the three virtual steering navigation techniques evaluated. Second, the results showed that the navigation technique had a significant effect on anticipation mechanisms. In a nutshell, virtual navigation techniques are not able to generate the same anticipation mechanisms that the ones observed in real and virtual walking, yet, the potential impact on the user has still to be explored. Nevertheless, we believe that by gathering knowledge about how users interact and behave in VEs, researchers and practitioners will be able to design new navigation techniques and control laws, based on laws governing human motor control, which could improve user comfort and the overall experience in VR.

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