Studying the Influence of Translational and Rotational Motion on the Perception of Rotation Gains in Virtual Environments

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ABSTRACT

Rotation gains in Virtual Reality (VR) enable the exploration of wider Virtual Environments (VEs) compared to the workspace users have in VR setups. The perception of these gains has been consequently explored through multiple experimental conditions in order to improve redirected navigation techniques. While most of the studies consider rotations, in which participants can rotate at the pace they desire but without translational motion, we have no information about the potential impact of the translational and rotational motions on the perception of rotation gains. In this paper, we estimated the influence of these motions and compared the perceptual thresholds of rotations gains through a user study (n = 14), in which participants had to perform virtual rotation tasks at a constant rotation speed. Participants had to determine whether their virtual rotation speed was faster or slower than their real one. We varied the translational optical flow (static or forward motion), the rotational speed (20, 30, or 40 deg/s), and the rotational gain (from 0.5 to 1.5). The main results are that the rotation gains are less perceivable at lower rotation speeds and that translational motion makes detection more difficult at lower rotation speeds. Furthermore, the paper provides insights into the user's gaze and body motions behaviour when exposed to rotation gains. These results contribute to the understanding of the perception of rotation gains in VEs and they are discussed to improve the implementation of rotation gains in redirection techniques.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**.

KEYWORDS

Virtual Reality, Motion Perception, Rotation Gains

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1 INTRODUCTION

In most Virtual Reality (VR) setups, navigation is required to explore Virtual Environments (VEs). One group of techniques, named redirection techniques try to optimize the trade-off between the size of the physical workspace while keeping real walking to explore VEs [Nilsson et al. 2018]. They rely either on the manipulation of users virtual and physical motion or the manipulation of the VE by altering its inner structure. The most common redirection method relies on using a non-isomorphic mapping between real and virtual user rotations (i.e. rotation gains) that enable subtle reorientation of the user in the Real Environment (RE). The discrepancies between physical and virtual movements require understanding the limits users can detect or not the motion differences (i.e. detection thresholds (DT)).

DTs are important for implementing redirected walking controllers as they provide insights about the perceptibly of gains as they must be subtle to users. Since rotation gains can be influenced by several factors such as the amount of rotation to perform [Bruder et al. 2009] or the Field of View [Williams and Peck 2019], they remain an active topic in VR research. Most of the experiments assessing the perception of rotation gains are based on physical rotations where users could rotate at their desired pace without any virtual translational motion added. Neth et al. showed that users are less sensitive to curvature gains while walking in VR at slower speeds [Neth et al. 2012]. In contrast, little is known about the sensitivity to rotation gains under particular experimental conditions: (1) while varying the rotational speed and (2) in the case of a virtual translation combined with users' rotational motion. In addition, recent studies have investigated the impact of rotations gains in 360° video-based telepresence systems [Matsumoto et al. 2020; Zhang et al. 2018]. In such systems, the combination of virtual translation of the mobile platform and user rotation in the workspace could occur, but they only investigated separately their impact. Thus, it remains unclear the potential influence of combined virtual translational and rotational motion on the perception of rotation gains.

This paper presents a perceptual study assessing the perception of rotation gains, in which participants had to discriminate the difference between their virtual and real rotations across several translational and rotational motions. Participants performed physical rotations in a virtual forest with two types of virtual translational motion (with or without) as well as three different rotational motions (20, 30 and 40 degrees per second). We recorded their body movements and gaze activity to study the effect of the experimental conditions on users' behavior. We assessed for each participants and conditions their gain DTs. Our main hypothesis was that the translational and rotational motions would impact participants DTs and users behaviors. The results of this study contribute to the understanding of human perception in VEs and provide insights about potential improvements in redirection techniques controllers, and in particular implementation of rotation gains in VR systems.

2 RELATED WORK

2.1 Amplified Head Rotation Gains

Redirection techniques often require scaling users' movements to allow them to remain in the workspace. A common approach is to modify the control/display ratio by applying a "gain". For instance, it is possible to scale head movements with a rotation gain ($g_r \in \mathbb{R}$), that is defined by the ratio between the virtual rotation $R_{virtual}$ and the physical (real-world) rotation R_{real} performed by the users: $g_r = \frac{R_{virtual}}{R_{real}}$. Then, a rotation gain (different than 1) alters the rotation of the virtual camera with respect to the physical rotation of the user: $R_{virtual} = R_{real} \times g_r$. A rotation gain $g_r > 1$ will result in a faster virtual camera rotation than the user's head rotation whereas a rotation gain $g_r < 1$ will result in a slower virtual camera rotation than the user's head rotation [Steinicke et al. 2010]. In most implementations in VR setups, rotation gains are applied on the yaw axis [Razzaque et al. 2001], but it is worth noticing that they can be applied as well on the pitch and roll axes [Bolte et al. 2010]. Although the gain is, in general, applied continuously and constantly (i.e. same value of g_r during the whole head rotation), there exist other ways to apply rotation gains if the amount of rotation to perform is known *a priori* [Congdon and Steed 2019; Zhang and Kuhl 2013]. In the rest of the paper, we will only consider constant rotation gains based on head's movements applied on the yaw axis.

In order to make rotation gains usable in VR, they should be as subtle as possible so that they minimize break of presence [Schmitz et al. 2018] and cybersickness [Hildebrandt et al. 2018]. To this end, many research work focused on the impact of different experimental conditions on the perception of head rotations gains in VR. For instance, the type of rotation [Jerald et al. 2008; Steinicke et al. 2010], the amount of rotation to perform [Bruder et al. 2009], the gain implementation [Congdon and Steed 2019; Zhang and Kuhl 2013], the impact of visual [Bruder et al. 2012b; Paludan et al. 2016] or auditory cues [Nilsson et al. 2016; Serafin et al. 2013] or distractors [Peck et al. 2009; Williams and Peck 2019], the impact of restricted Field of Views [Bolte et al. 2010; Brument et al. 2020; Williams and Peck 2019], difference between CAVE and HMD (Head-Mounted Displays) [Ragan et al. 2016], for video-based 360° telepresence systems [Matsumoto et al. 2020; Zhang et al. 2018], different locomotion interfaces [Bruder et al. 2012a] or even the method to estimate users perception of rotation gains [Hutton et al. 2018] have been explored so far. [Langbehn and Steinicke 2018; Nilsson et al. 2018] survey these studies and you can refer to them for further information.

Applying rotation gains in VR will modify the visual information that users have while navigating, creating a conflict between the amount of real rotation performed and the visual flow. We describe visual control of human locomotion in the next section.

2.2 Motion Perception in VEs

When navigating in real and virtual environments, the human visual system has a major role since it gathers information of the surrounding environment. It enables walkers to know about their position in the environment as well as their relative motion with respect to the other elements in the environment. Gibson introduced the ecological theory that describes the environment-agent system which is characterized by the inter-relation between the perception of the environment and observers' actions within this environment (perception-action loop) [Gibson 1979]. In his theory of direct perception, he explained that the visual stimulus provided by the environment is substantial enough to indicate the action an agent can performe within this environment.

In VEs, some studies demonstrated that steering behavior can be altered while walking with a HMD, either by shifting the Field of Expansion [Sarre et al. 2008] or modifying the field of view patterns [Chou 2005]. The particularity of navigation in VEs is that navigation techniques that don't require walking can be used. Thus, navigation techniques enhance vection (i.e. a conscious experience of self-motion [Palmisano et al. 2015]), which is induced by optokinetic stimulation and other sensory systems such as the vestibular one. Then, to generate self-motion illusions in VR setups, sensory stimulation is recommended (the reader is referred to [Riecke 2010] for a review).

Regarding rotation, vection can be increased by using a physical platform [Marchal et al. 2011; Rietzler et al. 2018]. The head and neck play a role in the perception of rotational movement. Simulating neck through vibrations helps the perception of rotational, and the relation between the head position relative to the trunk affects Vestibulo-Ocular Reflex (VOR) [Panichi et al. 2011]. While the importance of rotational cues for efficient spatial updating in VEs has been demonstrated [Chance et al. 1998; Ruddle and Lessels 2006, 2009], the importance and impact of translation cues is still not clear [Ruddle 2013].

Regarding translation cues, research work showed that the absence of embodied translational cues yielded to a lower navigation performance than with translational body-based cues [Nguyen-Vo et al. 2019]. In addition, translation gains can alter walking biomechanics, where the non isometric mapping between real and virtual movements led to deviated parameters of biomechanics compared to the ones with real walking [Janeh et al. 2017]. Neth et al. also demonstrated that the walking speed influence the sensitivity to curvature gains, where the slower the walking speed, the smaller the curvature radius is required [Neth et al. 2012]. The use of haptic feedback can also improve the perception of self-motion, allowing users to less under-estimate the angle turns during navigation [Lécuyer et al. 2004].

Previous work investigated the perception of rotation gains, considering the influence of several factors such as the amount of rotation or the Field of View. However, while being fundamental aspects of navigation in VEs, the influence of both the speed at which users had to perform the rotation and the virtual translation component while physically rotating have never been studied. The objective of our paper is then to assess the influence of translational and rotational speed on the perception of rotation gains in VEs.

3 USER STUDY

In this experiment, the goal was to assess the effect of translational and rotational motions on the perception of rotation gains. It was inspired by similar user studies performed to assess the perception of rotation gains without [Bruder et al. 2009; Steinicke et al. 2010] or with translation [Neth et al. 2012].

3.1 Design and Hypothesis

We conducted a 2 **Translation Speed** (no Translation (nT): 0m/s; with Translation (T): 1.4m/s) x 3 **Rotational Speed** (20°, 30°, 40° per seconds) within-subjects experiment to estimate DTs of rotation gains with or without virtual translation and varying the rotational speed. While most of the previous studies have assessed the perception of rotation gains by turning in place without virtual translation motion, we decided to investigate whether virtual translation could influence the perception of rotation gains, as it has been demonstrated that perception of curvature gain is influenced by the walking speed [Neth et al. 2012]. Moreover, most previous studies did not control the speed at which users performed the rotation. That is why we decided to control this factor by varying the rotational speed. We wanted to see whether turning faster or slower could influence the perception of rotation gains. The experiment only considered two translational conditions, as they relate to more common cases during VR locomotion, either stop or at comfort locomotion speed. In order to guarantee not too long experiment session, we decided to rather have more rotational speed to assess than translational speed for several reasons. We believed that the rotational speed would have more impact than the translational speed and therefore we wanted to have more values to assess regarding the rotational speed. In addition, since the impact of virtual translation has not been assessed yet, we wanted to first investigate only one translational speed in order to have a first comparison between with or without translational speed.

Six rotational gains ($g \in [0.5, 0.7, 0.9, 1.1, 1.3, 1.5]$) were considered in the experiment. For each combination (translation speed *times* rotation speed *times* gain) we considered four repetitions (two leftwards and two rightwards). Table 1 reports the amount of rotations participants had to perform in both real and virtual environments depending on the rotation speed and the gain. Based on our analysis, we hypothesized that translational and rotational speeds could alter participants perception and precisely: **[H1]** adding a virtual translational motion would help users to better discriminate the rotation gains; **[H2]** the slower the rotation speed, the higher the PSE and DTs are; **[H3]** gaze and body segments behavior would be modified by the translational and rotational speeds as well as the gains.

Table 1: Real rotation (in degrees) that participants had to perform with respect to the rotational speed and the gain. Since each trial lasted 3 seconds, the virtual rotations to perform were respectively 60, 90 and 120 degrees for the 20°, 30° and 40° rotational speed conditions.

Rotational Speed / Gain	0.5	0.7	0.9	1.1	1.3	1.5
20° (60° virtual rotation)	120	85	67	55	46	40
30° (90° virtual rotation)	180	129	100	82	69	60
40° (120° virtual rotation)	240	171	133	109	92	80

Figure 1: Left - User wearing the HTC Vive Pro Eye HMD equipped with a wireless module, one HTC Vive tracker located at the pelvis and one HTC Vive controller. Right - User's point of view of the VE during the experiment. The black arrow indicates the direction of the turn. The sight and pink sphere were used for calibration purposes).

3.2 Participants and Apparatus

14 participants (8 males, 6 females) aged between 21 and 53 years old (26.43±7.4, mean±SD) achieved the experiment. 5 participants reported having regular use of VR and HMD, 7 few times, and 2 never. Half of the participants had regular experiences with 3D videos games. We assessed their dominant eye and dominant foot through the questionnaire proposed by [Coren et al. 1979]. 10 participants had right eye and foot dominance whereas 4 had left dominance. They signed an informed consent form and were naive to the purpose of the experiment. The study was conformed with the standards of the declaration of Helsinki. All participants were able to finish the experiment.

The virtual environment was developed with Unity3D. We used a Vive Pro Eye HMD (resolution of 1440 x 1600 pixels per eye and a 110 degrees diagonal Field of View). The experimental platform was guaranteed to run at the minimum of the HMD's frame-rate (90Hz). We used the Vive Wireless Adapter[1] to avoid cables, as it could eventually disturb participants while performing the task (Figure 1).

The VE consisted of a large forest designed with Green Forest Unity 3D asset[2]. The VE enabled generation of motion flow during virtual translations applied while participants were physically rotating. A virtual black cross on the ground indicated the center of the physical workspace and was used for calibration purposes between

[1] https://www.vive.com/eu/accessory/wireless-adapter/
[2] https://assetstore.unity.com/packages/3d/environments/fantasy/green-forest-22762

trials. A virtual sphere with a diameter of 2.5cm was displayed in the VE and represented the target that participants had to follow.

3.3 Procedure

In our experiment, participants had to perform two different tasks: a proprioception task to assess the ability of users to estimate turning without any instructions and a perception task where we assessed the perception of rotation gains with and without virtual translation. The perception task was the main purpose of our study, in which we investigated the perception of gains whereas the proprioception task was to guarantee that users were able to accurately perform rotations before the perception task. We used a One Alternative Forced Choice (1AFC) task in which users are exposed to one stimulus (i.e., a rotation gain lower or higher than 1) and they are forced to choose an answer from a question with two potential answers, in our case determining whether the virtual rotation was **faster** or **slower** [Prins et al. 2016]. In order to avoid cybersickness due to the use of rotational gains and a high number of trials, we separated the experiment into two sessions separated each of at least 24 hours. Each session included one proprioception task and one condition (nT or T) of the perception task.

3.3.1 Beginning of session. Participants started by reading and signing a consent form that described the experimental protocol. Then, they filled a Simulator Sickness Questionnaire (SSQ) [Kennedy et al. 1993] and a demographic questionnaire (age, gender, amount of experience playing video games and exposure to VR).

3.3.2 Proprioception task. Participants started with the proprioception task. Participants were immersed in a virtual forest and were asked to perform leftwards or rightwards (direction) 90 degrees turns with or without vision (vision mode). In the without vision mode, we screen was blacked-out so that users did not have any visual cues from the environment. They performed 8 trials (2 repetitions x 2 directions x 2 vision mode) with the following procedure: (1) Participants were placed at the center of the workspace (indicated by the virtual black cross); (2) They had to align their body with a virtual sphere placed two meters in front of them (i.e. two meters forward from the black cross and position and at the user's height). A virtual black sight following head movements was displayed to help participants to aim at the sphere; (3) A text indicated the vision mode condition (with or without) and a black arrow indicated the direction of the turn (left or right). Once this calibration phase was done, they had to press the Vive controller's trigger to notify that they were ready to perform the trial; (4) After one-second countdown, the sphere, the text and the direction arrow were hidden and participants could start their 90 degrees rotation; (5) They had to press again the controller's trigger to indicate they finished their turn.

3.3.3 Perception task. Participants performed first 4 training trials using the maximum and the minimum gains in order to guarantee that they understood the task. Then, they performed four randomized blocks of 18 trials (3 rotational speeds x 6 gains, each combination is tested once per block). Leftwards or rightwards rotations were randomized during the task. Before each block, the eye-tracking system was calibrated using the native calibration procedure. Each trial followed the following procedure: Steps 1 and 2 are the same as for the proprioception task; (3) We indicated during one second with a virtual black arrow the direction of the sphere movement, then the direction arrow disappeared and the automatic motion started according to the translation condition (nT or T):

- nT - the sphere moved during three seconds leftwards or rightwards at the given rotational speed set for the trial. Participants had to align their whole body in order to always be facing the sphere until the sphere movement was done.
- T - an automatic constant virtual translation (1.4m/s) was added during the trial. The sphere and the participants started to perform a 2 meters forward virtual translation, then the sphere starting to move for three seconds leftwards or rightwards at the given rotational speed set for the trial. Participants had to align their whole body in order to always be facing the sphere until the sphere movement was done. To end the motion, we added a one-second forward virtual translation.

For both nT and T conditions, we guaranteed that the user's full body was aligned with the sphere by checking during the trial user head and pelvis orientation with the virtual sphere. At the end of the trial, the VE faded to black and participants had to answer the following forced-choice question: "I felt that my virtual rotation speed was (faster or slower) than my real one.". After a block, participants had to answer the following question: "On a scale of 0–10, 0 being how you felt coming in, 10 is that you want to stop, where are you now?". This question was first introduced in a research work assessing users' susceptibility to cybersickness [Rebenitsch and Owen 2014] and was reused in other experiments assessing cybersickness during navigation (e.g., [Fernandes and Feiner 2016]). In our experiment, this question allowed us to monitor during the experiment users comfort between blocks. We refer to this question as Fast-SSQ in the rest of the paper. After two blocks, participants had to take at least a 5 minutes break to mitigate cybersickness.

3.3.4 End of session. At the end of the session, participants filled a post-SSQ. Then, we asked participants a multiple choice question: "Which information did you prior the most to detect the rotation gain?" with the following answers: Body orientation; The ability to gaze the sphere; Motion of the sphere; My rotation speed; Rotation of the virtual environment; Salient elements of the virtual environment; Steps done during the task. The objective was to identify which features participants would rather rely upon perform the perception task. In total, one session took approximately 45 minutes.

3.4 Data Analysis

In the proprioception task, we collected in total 224 trials (14 users x 2 sessions x 2 vision modes x 2 directions x 2 trials). For each participant, condition and body segments (head and pelvis), we computed the relative error (in degrees) of the estimation of 90 degrees rotations. In the perception task, we collected in total 2 016 trials (14 users x 2 translation types x 3 angular speeds x 6 gains x 2 directions x 2 trials).

For each participant, we computed the probability of answering "Faster" from the 1AFC question $P(g_n; faster)$ for each gain, translation type and rotational speed. We used the Quickpsy package in

R (version 0.1.5.1) to compute participant's PSE and 25% and 75% DTs [Linares and Lopez-Moliner 2016]. It allows fitting psychometric curves based on the experimental data by direct maximization of the likelihood. These psychometric functions follow the form $\psi(g_n) = \gamma + (1 - \gamma - \lambda) * F(x)$, where γ is the guess rate, λ the lapse rate and F the cumulative normal distribution function. We set γ at 0 and the lapse rate was estimated as a parameter of F.

To analyse the head orientation, we computed the amplitude of the head as the unwrap arc-tangent of the head orientation. Then we resampled at 90Hz the data and performed a temporal normalization to study the evolution of head amplitude over time and analyse the participants turning behavior through the different experimental conditions. To this end, we used the Statistical Parametric Mapping (SPM) method [Friston et al. 2007]. This analysis allows comparing time-series data of different trials taking into account their variability at each time-step. We computed the baseline movement of the sphere that was constant across experimental conditions in order to compare the conditions with respect to the theoretical movement participants should have performed. We also recorded the delay (in degrees) participants had at the end of the trial (i.e. how far from the sphere they were when this one ended its trajectory).

Eye-tracking data was captured at 90Hz and filtered using a Butterworth low-pass filter of order 4 to filter high-frequency artifacts (higher than 15Hz). Instead of using the raw eye-tracking data, our analysis considered the angular error between the center of the sphere and the eye direction. For each block, the first second for all the trials in the T condition, in which users were instructed to gaze the target sphere while it was describing a forward motion, was used to correct any rotational offset that could be introduced by an inaccurate calibration. The offset was computed by averaging all data points (30s of data per user). Using the corrected angular error data, for each trial we computed the ellipse that fitted the 95% of the data samples. The ellipse fit provides insights into the spread and accuracy of the user's gaze. The eye-tracking data from one user was not exploitable due to errors in the recordings and two users were excluded from the analysis as they presented unique behaviours (higher variability and lower precision). From the remaining data, 40 trials were excluded from the analysis when the width and x-offset were higher than 3 standard deviations. The total number of observations was 1541.

From the pre and post SSQ data gathered before and after each session, we computed the pre and post SSQ score accordingly to the methodology described in [Kennedy et al. 1993]. We also computed a delta SSQ score for each scale (i.e., post SSQ score minus pre SSQ score) to have insights into the cybersickness variations after each session.

Assessing the effect of the experimental conditions (translation speed, rotational speed) on independent variables, we performed analyses of variance (ANOVA) with repeated measures. To analyse and compare PSE and DTs across conditions, we used the bootstrap comparison provided by the Quickpsy package. Shapiro-Wilk test was used to test the normal distribution of the data. When appropriate, we applied Greenhouse-Geisser adjustments to the degrees of freedom, to avoid any violation of the sphericity assumption. Post-hoc analyses were based on pairwise t-tests with Bonferroni corrections. Friedman test and post-hoc pairwise Wilcoxon tests with Bonferroni were used to analyse subjective data from questionnaires. All reported significant results had a p-value lower than 0.05.

3.5 Results

3.5.1 PSE and DTs. With the 1AFC question answers, we fit psychometric curves by turn direction, session, translation and rotation type. We did not find any significant effect of the turn direction or the session on the PSE and DTs, thus we group the answers only considering the translation (nT, T) and rotation type (20°, 30° ,40°) (Figure 2). Table 2 reports the averaged PSEs and DTs per conditions. For the translational motion (10th and 11th lines of Table 2), bootstrap comparisons of PSE and DTs showed no effect between nT and T conditions, resulting in similar discrimination of rotation gains with or without virtual motion. For the rotational motion (7th, 8th and 9th lines of Table 2), bootstrap comparisons showed an effect where PSE were significantly lower for the 40° rotation (0.99) than the 30° (1.11) and 20° (1.12) ones as shown in Figure 3. 25% DTs were significantly higher for the 40° rotation (0.72) than the 30° (0.58) or 20° (0.64) ones, and 75% DTs were significantly lower for the 40° (1.19) than the 30° (1.36) or 20° (1.35) ones. These results mean that users tended to underestimate the rotation gains when the rotation speed was lower. Considering the interaction between translational and rotational speed (1st to 6th lines of Table 2), bootstrap comparisons showed a significant effect where the PSE for the nT20° condition had the highest values. This means that users underestimated the most the rotation gains at the lowest rotation speed without virtual translation motion.

3.5.2 Body segments behavior. Figure 4 shows the averaged normalized head amplitude depending on the rotational speed and gain. SPM analysis showed an effect of the gain on these time-series during the turn. Post-hoc tests demonstrated that the smaller the gain, the higher the delay with the baseline (movement of the sphere) during the turn. This observation can be seen by the rightwards shift with respect to the black line, where high gains are less shifted than the low ones. Thus, it is easier for users to align themselves with

Table 2: The 25%, PSE, and 75% threshold gains computed from the psychometric curves. Deviance (D) and p-value (p) represent the goodness-of-fit. DTs and PSE are sorted by translation and rotation types.

		25%	PSE	75%	D	p
nT	20	0.72	1.16	1.42	17.30	1.00
	30	0.51	1.01	1.36	5.18	1.00
	40	0.71	0.94	1.17	3.36	0.91
T	20	0.49	0.98	1.30	6.55	1.00
	30	0.55	1.06	1.36	5.33	1.00
	40	0.75	1.03	1.26	1.65	1.00
20		0.64	1.12	1.35	0.09	1.00
30		0.58	1.11	1.36	1.98	0.97
40		0.72	0.99	1.19	0.69	1.00
nT		0.66	1.08	1.33	21.64	1.00
T		0.64	1.07	1.32	8.89	1.00

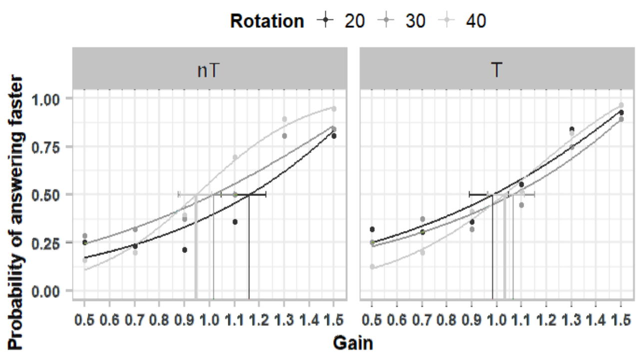

Figure 2: Psychometric curves from the pooled results of the 1AFC question per translation (nT and T) and rotation type (20° in red, 30° in green and 40° blue). The PSE with a 95% confidence interval is indicated for each curve.

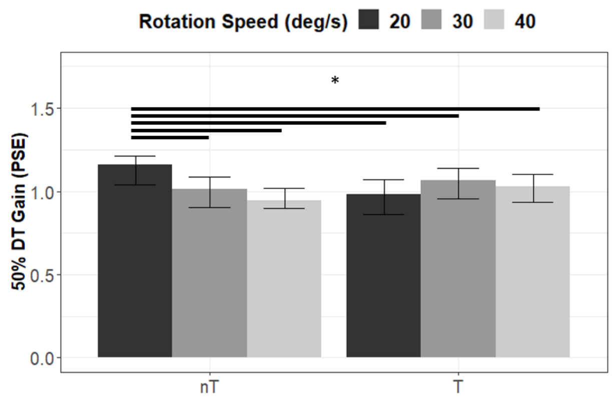

Figure 3: PSE (middle) gain thresholds per translation type and angular speed. Significant pairwise comparisons are indicated by the black lines ($p < 0.05$).

the sphere for smaller rotation speeds and a gain higher than one. However, no difference was observed between nT and T conditions that had similar profiles.

We can also observe on Figure 4 that, the higher the rotation speed, the higher the delay to face the sphere. Regarding the delays participants had with respect to the sphere at the end of the trial, a 3 way ANOVA (translation type x angular speed x gain) showed that the angular speed $F_{1.31,14.41} = 155.89$, $p < .001$, $\eta^2 = .94$ and the gain $F_{1.56,17.11} = 22.10$, $p < .001$, $\eta^2 = .67$ had an effect on the delays. There was an interaction effect between the angular speed and the gain $F_{2.63,28.97} = 21.25$, $p < .001$, $\eta^2 = .66$. Post-hoc analyses showed that the higher the angular speed the higher the delay ($p < .05$), the smaller the gain the higher the delay ($p < .05$).

3.5.3 Gaze analysis. Figure 5 depicts the gaze distribution when grouping the data based on the direction and the translation conditions. Participants' gaze had an asymmetry for the left and right conditions (i.e., a shift with respect to the center of the sphere at (0,0) coordinate), suggesting a gaze behind the target, while an increased dispersion for the conditions in which there was no translational motion. For the statistical analysis, we only discuss the horizontal indicators (width and x-offset of the ellipse), as the object to follow did not exhibit any vertical motion.

For the ellipse width, a full factorial ANOVA analysis of direction × gain × translation × rotation showed a main effect of gain $F_{1.76,17.63} = 14.47$, $p < 0.001$, $\eta_p^2 = 0.59$, and an interaction effect between translation and rotation $F_{1.98,19.77} = 17.74$, $p < 0.001$, $\eta_p^2 = 0.64$ (see Figure 6). Post-hoc tests showed that the width of the ellipse was significantly higher for the 1.5 gain condition ($M = 4.34$;$SD = 1.35$) than for the others $M = [3.30..3.62]$;$SD = [1.07..1.24]$, which suggests that gaze activity was more spread on the horizontal axis at the highest gain than the others. For the interaction effect, post-hoc tests (only significant comparisons are reported $p < 0.05$) revealed that the increase of the rotation speed had a higher increase of the width of ellipse for the nT condition (20° < 30° < 40°) compared to the T condition (20° < 30°, 20° < 40°). Moreover, the effect of the translation motion was significant at the 40° condition but not for the 20° and 30° conditions.

For the ellipse x-offset analysis (i.e., offset from the center of the sphere to track), as we did not observe an effect of the direction when mirroring left trials data, for the sake of simplicity, we aggregated repeated samples by considering the mirrored values. The ANOVA analysis showed a main effect for gain $F_{1.90,18.99} = 9.13$, $p < 0.01$, $\eta_p^2 = 0.48$ and rotation speed $F_{1.15,11.46} = 8.74$, $p < 0.05$, $\eta_p^2 = 0.47$ (see Figure 7). Post-hoc tests suggest that the x-offset increases as the gain increases, although not all pairwise comparisons are significant. The strongest effects are found between the lowest and the highest gains, 0.5 ($M = 0.09$;$SD = 0.93$) and 0.7 ($M = 0.22$;$SD = 1.27$) conditions have a significant x-offset smaller than conditions 1.3 ($M = 0.51$;$SD = 1.06$) and 1.5 ($M = 0.60$;$SD = 0.95$). Regarding rotation speed, data also suggests that as the rotation speed increases the x-offset decreases. Post-hoc tests showed that the 40° condition ($M = 0.21$;$SD = 0.89$) was significantly smaller than the 20° ($M = 0.49$;$SD = 0.72$) and 30° ($M = 0.41$;$SD = 0.81$) conditions. Finally, we also observed two interactions effects between the translation and rotational speeds $F_{1.41,14.08} = 5.45$, $p < 0.05$, $\eta_p^2 = 0.353$ and between the gain and the translation speed $F_{3.10,31.05} = 7.53$, $p < 0.001$, $\eta_p^2 = 0.43$. Regarding the first interaction (see Figure 7 right), post-hoc tests showed that the T40° condition was the one exhibiting significantly less offset compared to the other combinations (no other significant pairwise comparison). Regarding the second interaction (see Figure 7 left), although the visual inspection suggests that having translational motion decreases the offset as the gain decreases, post-hoc tests showed inconclusive results.

3.5.4 Questionnaires. Table 3 reports the average and the standard deviation of pre, post and delta SSQ scores for each scale (nausea, oculomotor, disorientation) and in overall, grouped by the session order (first, second). Besides, we also noticed that there was no significant effect of session or translation type on every scales of pre SSQ scores, meaning that the users' state was equivalent at the beginning of both sessions and conditions. Thus, we focused on the statistical analyzes of delta scores as they measure the increase after one session.

There was no significant effect of the translation type on SSQ delta score for the nausea $F_{1,13} = 0.53$, $p = 0.48$, oculomotor $F_{1,13} = 2.43$,

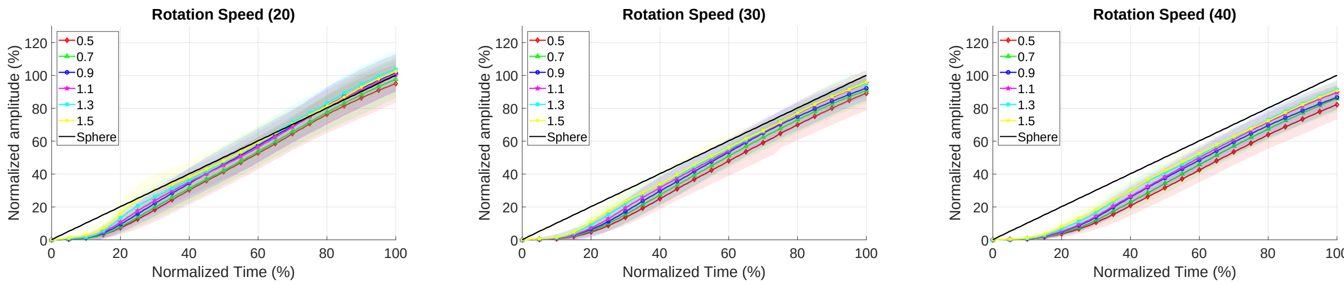

Figure 4: This figure shows typical temporal evolution of mean and standard deviation of normalized head amplitude for each Rotation Speed (20° left, 30° center and 40° right), and gains (from 0.5 to 1.5 and the theoretical baseline). There is an effect of the gain during the whole turn duration (the F value for the factor gain is higher than the F^* computed).

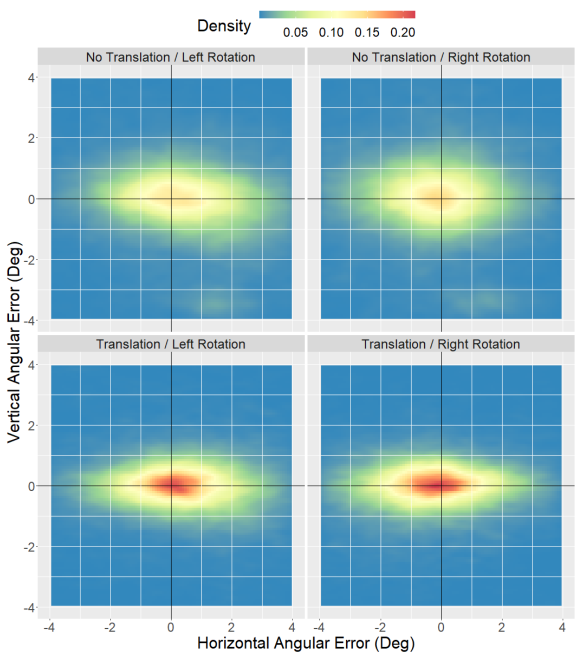

Figure 5: Gaze error density plots when the sphere was rotating. The $(0,0)$ represents the center of the sphere to track.

p = 0.14, disorientation $F_{1,13}$ = 0.08, p = 0.77 and total $F_{1,13}$ = 0.20, p=0.65. However, there was a significant effect of the session order on SSQ delta scores for the nausea $F_{1,13}$ = 8.86, $p < 0.05$, $\eta_p^2 = 0.40$, disorientation $F_{1,13}$ = 7.41, $p < 0.05$, $\eta_p^2 = 0.17$ and total $F_{1,13}$ = 8.19, $p < 0.05$, $\eta_p^2 = 0.13$ scales. Post-hoc analyses showed that the delta scores were significantly lower after the second session than the first one.

Figure 8 reports the scores of the fast-SSQ answers after each block and for each session. Mean and standard deviation scores after a block of 18 trials performed were respectively 0.96 ± 1.78, 1.96 ± 1.90, 0.78 ± 1.72, 1.60 ± 1.93 for the first, second, third and fourth blocks. We found no effect of session ($F_{1,13}$=0.88, p=0.27) nor block number ($F_{1,13}$=2.58, p=0.09) on the fast-SSQ scores.

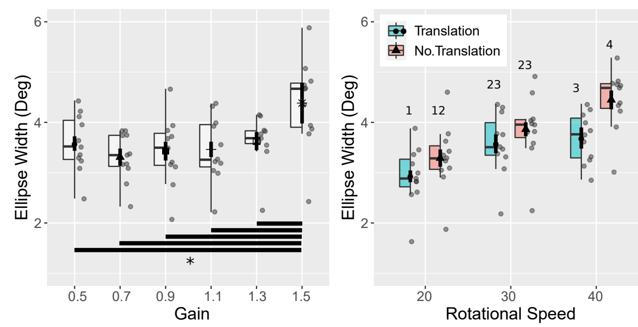

Figure 6: Left - Ellipse width for the gain factor, significant pairwise comparisons are indicated by the black lines ($p < 0.05$). Right - Ellipse width for the translation and rotational factors. Post-hoc tests are reported using superscripts. Two levels sharing the same superscript are not significantly different.

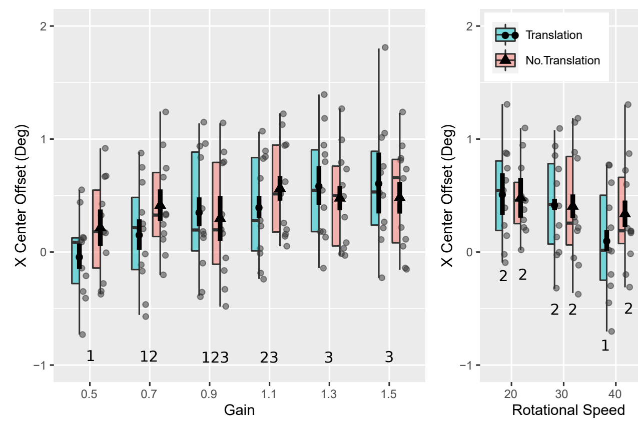

Figure 7: x-offset for the interaction effects between translation condition on gain (left) and rotation speed (right). Post-hoc tests are reported using superscripts. Two levels sharing the same superscript are not significantly different.

Regarding the results of the multiple choice question we asked at the end at the session, a chi-square test showed that both distributions of the answers for the static and moving conditions were

Table 3: Pre, post and delta scores computed per session for each scale (nausea, disorientation, oculomotor and total).

Session		Nausea	
	pre	post	delta
1	19.08±20.83	37.47±15.63	18.39±22.90
2	18.39±21.64	21.19±13.62	2.79±25.02
		Disorientation	
	pre	post	delta
1	12.80±12.76	61.64±42.19	48.83±41.19
2	13.73±16.39	25.85±24.32	12.11±27.14
		Oculomotor	
	pre	post	delta
1	25.98±21.79	36.81±16.24	10.82±21.58
2	20.03±25.85	23.82±14.82	3.79±25.18
		Total	
	pre	post	delta
1	18.96±17.93	37.66±16.94	18.70±19.62
2	16.56±20	20.57±12.51	4.00±23.35

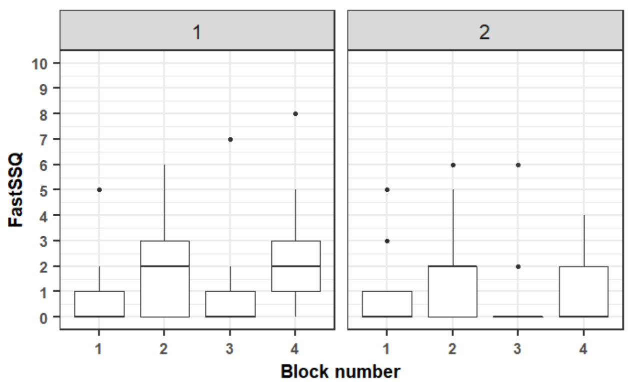

Figure 8: Boxplot of the fast-SSQ answers after performing a block (grouped by session 1 and 2).

dependent ($\chi^2(6) = 8.50$, $p = 0.20$). Numbers of answers per items were (number selected after nT / number selected after T): Body orientation (7/6); The ability to gaze the sphere (2/7); Motion of the sphere (7/10); My rotation speed (9/12); Rotation of the virtual environment (6/8); Salient elements of the virtual environment (2/0); Steps done during the task (10/4). Note that we can note that the most selected item for the nT condition was Steps done during the trial" and "The ability to gaze the sphere" for the T condition.

3.5.5 Proprioception Task Results. Table 4 reports the relative angle error from the 90 degrees turns for each conditions. A three way ANOVA (direction of turn x vision mode x body segments) showed that the direction of turn $F_{1,13} = 15.80$, $p < 0.01$, $\eta^2 = 0.55$, and the body segment $F_{1,13} = 20.88$, $p < 0.001$, $\eta^2 = 0.616$ had an effect on the estimation of 90 degrees turn. We also found an interaction effect of the direction x body segment $F_{1,13} = 10.98$, $p < 0.01$, $\eta^2 = 0.45$, the body segment as well as direction x body segment x vision $F_{1,13} = 6.91$, $p < 0.05$, $\eta^2 = 0.34$. Post-hoc analyses showed that head error was higher than the pelvis one ($p < .05$), the error was higher for rightwards turns than leftwards turns ($p < .05$) and the highest error was the head during rightwards turns with vision ($p < .05$).

Table 4: Average turning error of head and pelvis from the proprioception task.

Turn direction	Vision	Head error	Pelvis error
Left	Without	-0.21(22.42)	2.32(11.93)
	With	2.58(17.48)	0.33(16.99)
Right	Without	9.89(11.00)	4.47(9.78)
	With	13.90(11.25)	8.91(11.97)

4 DISCUSSION

Our main objective was to assess whether translation and rotational speeds alter the perception of rotation gains in VEs. With the proposed study, we observed an effect of rotational speed, in which the lower the rotation, the less sensitive to the gains participants were, but also an interaction effect where condition nT20° was the configuration for which participants were the least sensitive. The experimental conditions also affected gaze and body segments behavior. We discuss in the following section these results.

4.1 Motion and Perception of Rotation Gain

While most of the studies related to the perception of rotation gains in VR excluded the translational component, it is important to consider it as it could bias the perception of rotation in the horizontal plane as demonstrated in both REs and VEs [Sarre et al. 2008]. We hypothesized that translational motion could improve the perception of heading and thus could make the detection of gain more easily because motion parallax contributes to the perception of heading during rotation [Li and Warren Jr 2000]. We did not find a global effect of the virtual translational motion on the perception of rotation gains, meaning that the addition of a virtual motion did not help users to discriminate the gains. One explanation might be that users could not rely on extra-retinal information to disambiguate the motion perception since they had to look at the sphere. However, we found an interaction effect between the translational motion and the 20° rotational motion which suggests that it might be easier to apply gain during small rotations performed by the user while virtually translating in the VE. Thus, our results do not support **[H1]**, since we did not find a global effect of translational speed. In particular the interaction effect between low rotational speed combined with translation made the detection of gains harder, which contradicts our initial hypothesis. The influence of translation on the perception of rotation gain is still unclear and further work is required (e.g assessing a wider range of speed, or comparing continuous and discontinuous motions) to investigate whether it could alter users' perception or not.

Regarding the impact of rotational component, results showed that users underestimated more rotation gains at lower speeds (i.e., it is easier to detect rotation gains as the rotation speed increases). Even though visual perception research supports that the faster the head is turned the less visual awareness of the environment, we suggest that staring at the sphere would have mitigated these effects.

In contrast, [Neth et al. 2012] investigated the influence of walking speed on the detection of curvature gain. They demonstrated that people are significantly less sensitive toward walking on a curved path when walking slower. These results found for curvature gains are in line with the ones we observed: users were significantly less sensitive to rotation gains when turning at a slower pace. It is worth noticing that it has been shown that angular velocity profiles can differ depending on the turn to perform and the gain applied [Dumontheil et al. 2006]. We also want to point out that, even though we found an effect of rotational speed, we are aware that there may be an interaction between the rotational speed and the amount of physical rotation to perform. Table 1 shows that both gain and rotation speed influenced the amount of physical rotation to perform. Thus, in some configurations, additional proprioceptive feedback was provided to users that may have helped users to better discriminate the rotation gains at higher rotational speeds, as it was already demonstrated in a previous experiment that showed that participants were better at discriminating rotations when the virtual turning angle is rather large [Bruder et al. 2009]. This might also explain why we noticed in the subjective data that users rather relied on proprioception since they reported using more the information of their number of steps performed during the task in the nT condition, showing that the amount of rotation performed might be a metric used by participants to discriminate the gains. Last, when looking at Table 2 and Figure 3, we can notice that the 30° breaks the values pattern for the T condition where its PSE is higher than the 20° or 40°. This is an unexpected but real effect as we expected to have either increasing or decreasing DTs as the rotational speed changes. We suggest that users may have more difficulty distinguishing rotations gains at an "average" rotational speed than the lowest and highest in our experiment. Thus, our results confirmed **[H2]**, but additional work is required to understand users' ability to detect rotation gains in VEs with experiments focusing on manipulation of optic flow. Especially, the interaction between the gain and the rotation speed of the sphere may have impacted the performance, since users perception may have been filtered in order to rely mostly on the rotational speed (a more salient cue than translation), thus leading to an inconsistency between virtual and real rotations.

4.2 Body Segments and Rotation Gain

Figure 4 shows the temporal evolution of head orientation over time by rotation speed and gains. The higher the rotational speed, the higher the delay is between the baseline (black line) and the average users' amplitude during the rotation. Since participants had no prior knowledge about the trial they should perform, they tended to be late in the rotation compared to the sphere rotation at high rotational speeds. This could explain also why participants tended to better discriminate at high rotational speed since they had to turn faster to catch up with the sphere. Thus, we suggest that the way users turn in studies investigating the perception of rotation gains should not be neglected as this delay could have been a bias to users to determine whether the rotation speed was faster or slower. For instance, some studies investigated the impact of body segment coordination with different navigation techniques [Brument et al. 2019]. Then, analyzing these coordination movements could lead to the design of new adaptive gains based on users' movements, knowing that head anticipation is an invariant of human locomotion that is also preserved while navigating in VEs.

In addition, we observed differences in gaze behavior across the different experimental conditions, in particular an effect of translation and rotational speeds on gaze patterns. Figure 5 showed that there was more eye dispersion on the horizontal axis when no virtual translation were applied. We suggest that the virtual translation then provided more visual information and helped users to better focus on the sphere. By combining this information with the DTs found, we could suggest that the gaze error could provide some additional information to detect whether a user might notice a gain applied or not.

The analyses revealed that the higher the gain and the rotational speed, the higher the dispersion of the gaze (Figure 6 left). We believe that gaze activity could be an interesting metric to understand how participants differentiate gains. As the movements of the sphere and the were different, the ability to gaze at the sphere could have been more difficult for highest and lowest gains. It is interesting to see that we did not find a symmetry in the ellipse width dispersion as the dispersion only increased significantly for the highest gains. Moreover, we found that the highest ellipse width was with the nT40 condition (Figure 6 right), but also that the higher the rotation speed, the easier users detected the gain. Thus, we could imagine detecting on the fly whether users are able to discriminate a gain or not based on their gaze activity in order to adapt or take advantage of gaze activity to modulate gains as it has been already done in some research work [Langbehn et al. 2018; Sun et al. 2018].

These results support **[H3]**, the experimental conditions having modified the gaze and body segments behavior, but future work should considering further analyses of gaze such as fixations and saccades.

4.3 Towards User-Centered Gain

Previous research work on the perception of rotation gains showed the impact of different experimental conditions such as the Field of View, the amount of rotation to perform or the addition of distractors. In our experiment, we showed the impact of additional experimental conditions: translational and rotational speeds. This information could be important in the implementation of rotation gains. For instance, instead of applying the gain constantly during the whole rotation, we could consider different implementations. Congdon and Steed showed that the implementation of the gain (constant vs linear vs delayed) can influence the perception of rotation gains [Congdon and Steed 2019]. It could be possible to consider different rotation gains transfer functions, considering as well the translational and rotational speeds. The use of virtual translation and real rotations could be considered in 360° video-based presence system [Zhang et al. 2018]. One example of a consistent implementation based on our results could be to increase the rotation gain when users are turning slowly and decrease it when they turn fast. In addition, we could imagine increasing slightly more the rotation gain when virtual motion is performed by the mobile platform. Having the ability to adapt the gain during navigation would eventually improve redirection controllers.

The use of virtual translation in our study was inspired by redirection techniques. In particular, redirected walking uses rotation gains while users are walking in the workspace. We could imagine that those paradigms could be used for other types of techniques that requires the use of virtual translation such as steering techniques. A recent research work showed that users tend to drift in the workspace while using steering techniques, reaching the boundaries of the workspace even though those techniques do not require physical translational movements [Brument et al. 2021]. Thus, the use of rotation gains during virtual translation could be interesting to manipulate users' movements and try to maintain them at the center of the workspace while navigating in the VE. In addition, rotation gains are used in 360° video-based telepresence systems [Matsumoto et al. 2020; Zhang et al. 2018]. They are based on combining virtual translation of the mobile platform and user rotation in the workspace. Thus our results provide additional insights into how gains should be applied in such scenarios.

Regarding cybersickness, we found no effect of the translation type (nT or T) or the session on the fast-SSQ scores (Figure 8), meaning that adding additional virtual translation in T condition was not inducing more cybersickness than in the nT condition. We can also notice that the lowest fast-SSQ scores are after the first and third block, which can be easily explained by the fact users should feel more comfortable at the beginning of the session and after the 5 to 10 minutes break occurring after the second block. However, we found an effect of the session on the delta and post SSQ scores, where cybersickness was significantly lower after the second session performed 24 hours later than the first one (Table 3). We can suggest that users had some adaptation to rotation gains, leading to lower post SSQ scores on the second session, similarly to users that can adapt to increased curvature gains through separated sessions [Bölling et al. 2019].

In addition to cybersickness data, adding supplementary metrics such as gaze, proprioceptive or body-segment behavioural or movement data in the design of rotation gains may be promising as they could be adapted to user behavior. Indeed, taking advantage of gaze movements in redirection techniques has been already explored. Saccadic suppression of images has been already used to subtlety reorient participants in the VE. They are based on the inability to detect changes, during or shortly after a saccade, in the location of a target when the change occurs immediately before [Bridgeman et al. 1975]. Some perceptual studies and redirection controllers have been published [Bolte and Lappe 2015; Langbehn et al. 2018; Sun et al. 2018], showing the potential of using gaze information for implementing rotation gains. Gaze activity could be then considered when designing the implementation of rotation gains while navigating in VR.

Even though the analyses of gaze and body segment in a perceptual study of rotation gains are quite unusual, our results are encouraging and we suggest that considering these metrics could be interesting in the study and implementation of rotations gains for two reasons: (1) they may provide a better understanding on users perception when rotation gains are applied and (2) these objective metrics can be gathered and analyzed on the fly during VR navigation so that we could imagine adaptive rotation gains based on these metrics.

5 LIMITATIONS AND FUTURE WORK

Our results provided insights into how users perception can be altered while varying motions in VEs, with practical implications for different applications and potential vistas for future work to improve redirection techniques in VR. However, there are also a few limitations of our current work, which may lead to additional research ideas that may be investigated in future work.

First, to improve knowledge about perception of rotation gains with virtual translations, further studies can be envisioned by varying the experimental factors. Additional levels of the linear speed can be considered (e.g. lower or higher speeds) and real translations (i.e. walking) could also be tested in which additional proprioception cues might play a role.

Second, other design choices can also be considered, such as the rotation gain implementation and the virtual environment. Apart from a constant gain, other rotation gain control laws could be considered as they could alter users' perception [Congdon and Steed 2019; Langbehn et al. 2019]. Furthermore, the environment could also play an important role on the gain detection as more "structured" environments (e.g., interior spaces like buildings) could make the detection easier.

Third, in this paper we proposed the analysis of gaze activity and body segments movements. However, additional data and further analysis are required to have a better understanding of how rotation gains can alter users' behavior during navigation in VR.

6 CONCLUSION

The study of the perception of rotation gains remains an active research topic in VR navigation. Understanding how users perceive those gains is necessary in order to implement subtle redirection techniques. Yet, it is important to consider the differences between the way the perceptual studies are performed, and the use of redirection techniques during navigation in virtual environments where gains are applied. In this paper, we proposed to study and assess the impact of combined translational and rotational motions on the rotation gains perception. The results of our experiment revealed that participants are less sensitive to rotation gains when the rotational motion decreases. Regarding the impact of translation, even though our results suggest that the combination of virtual motion with a low rotational speed tends to make the rotation gains more subtle. In addition, the body segments and gaze analyses showed that the translational and rotational motions but also the gains can alter users' behavior. These results open new perspectives and metrics about how users can detect rotation gains. To conclude, this paper provides new results on how users perceive rotation gains in VR that could be used to improve the implementation of rotation gains in VR setups. We believe that considering both rotation and translation motions of users as well as their body and ocular movements while navigating could be an interesting approach to improve the redirection techniques, using a user-centered approach to make those controllers more adapted to the users.

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