Can Haptic Feedback Improve the Perception of Self-Motion in Virtual Reality?

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Abstract

This paper describes an experiment which was conducted to evaluate the influence of haptic feedback on the perception of self-motion in virtual reality. Participants were asked to estimate the angles of turns made during a passive visual navigation. Sometimes, during a turn, a haptic feedback was sent to the dominant hand of the participants. This haptic feedback consisted in rotating the participants' fist by the same angular value as the visual turn.

The presence of haptic feedback globally influenced the performances of the participants. On average, with haptic feedback, the participants less under-estimated the angles the turns made in the visual navigation. These results suggest that the perception of self-motion could be improved in virtual reality by using an appropriate haptic feedback. Haptic stimulation during navigation could partially substitute for the missing information provided by proprioception and vestibular system.

1. Introduction

Navigation may be one of the "killer applications" [13] of immersive Virtual Reality (VR). Navigation in VR may be used for training (training of an airplane pilot, driving simulation, re-education and mobility training), for design (virtual visit of urban or architectural projects) or simply for fun (video games, theme parks).

In Virtual Environments (VE), navigation is simulated almost exclusively with visual stimulation. Most of the other sensory stimulations – which are usually present when navigating in real life – are generally absent in VR. The missing information concern mainly three different types of sensory feedback: the proprioceptive feedback, the vestibular feedback, and the copy of the corollar discharge.

This implies a sensory conflict between vision and the other sensory modalities involved and used when navigating. This sensory conflict may be responsible for cybersickness – a nausea phenomenon which is observed in many VR applications.

To cope with this problem as well as to improve the sensations of the users, VE designers and researchers have proposed the use of simulation platforms. These actuated platforms move the body of the user consistently with the visual motion [14]. However, the use of simulation platforms and/or other locomotion interfaces still remains expensive and complex.

The main objective of the present paper is thus to study the possibility to substitute for and/or simulate the missing information – mainly proprioceptive and vestibular sensations – with another sensory feedback: a haptic feedback sent in the user's dominant hand. Two theoretical questions are thus raised:

- Can haptic feedback substitute for the missing sensations of navigation in VR (i.e. proprioceptive and vestibular information)?
- Can haptic feedback improve the perception of self-motion, the memorization of a trajectory, and the creation of cognitive maps?

This paper presents a preliminary study that brings some answers to these questions. An experiment was conducted which used a simple haptic feedback in addition to a passive visual navigation in VR. The haptic feedback was sent to the participants in conjunction with the turns of the visual navigation. The haptic feedback consisted in rotating the participants' fist by the same angle as the actual visual rotation. We measured the influence of haptic feedback on the participants' perception and estimation of the angles the turns made in the visual navigation.

2. Related Work

Navigation in virtual reality requires the use of an efficient and appropriate Computer-Human Interface (CHI) [17]. Usually, the paradigm chosen makes full use of both the software's and the hardware's possibilities. Peterson et al. [13] studied the influence of the hardware device used on the VR navigation capacities. They compared the use of two different input devices: a joystick and an interface based on the active motion of

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the body (the Virtual Motion Controller or VMC). They showed that position control during navigation was slightly more precise with the joystick. But when using the VMC, participants proved more efficient at creating mental map of the VE – especially with complex environments.

Researchers have sometimes proposed additional tools on the visual modality in order to improve the navigation. Such tools are for example: virtual compass [15], visual landmarks [12], grids or accessible maps [5]. These tools are likely to improve the wayfinding of the user in the virtual world [5], as well as the creation of cognitive maps of the VE [12].

In few cases, the navigation paradigm uses a haptic device – i.e. force or tactile feedback – in order to increase the sensations of navigation. For example, force feedback joysticks [2] (or wheels) provide gamers with simple haptic effects when driving a car or any other virtual ship. Vibrations or resistance effects are sent back to the user in relation to the state of the ship or to some specific events (sliding, passing over grass, collisions).

Haptic feedback is also used for the guidance and mobility training of blind people in virtual [11] or real environments [3]. Today, several "augmented" blind canes detect obstacles in the real environment and generate an appropriate alarm feedback on the haptic mode [3]. The US Navy also developed a system based on a tactile feedback for the guidance of airplane pilots: the Tactile Situation Awareness System [16]. Vibrators, embedded in the pilot's jacket, stimulate the pilot's torso in various locations according to the plane's orientation. This system is helpful to reduce the visual workload of the pilot [16].

At last, virtual environments can make the user literally move by using a simulation platform [14]. Accelerations are stimulated in order to be perceived by the human vestibular system in addition to the visual information. These stimulations are likely to improve the immersion of the user and the perception of self-motion during navigation [14].

However, many of the differences between virtual and real navigation are due to a lack of knowledge about the human cognitive processes involved in navigation. In this context, virtual reality provides an efficient tool that has been largely used to study human perception and spatial cognition [4] [6] [8] [9] [13].

Humans feel the sensations of motion from different sensory modalities (see review by Harris et al. [9]). Self-motion information may come from the vestibular sense, the proprioceptive sense or the efferent copy of the muscular command. Information may also be provided by vision, audition or even smell. Vision is a major actor in the perception of self-motion. For example, the *vection* phenomenon is a strong illusion of motion induced by an optic flow covering a large visual field [7]. However, Ivanenko et al. [10] have shown that without vision, the brain still succeeds in perceiving and estimating motion, even in the case of a passive motion. Rotation values were indeed successfully extracted by blindfolded people from several bi-dimensional trajectories experienced under different conditions of passive motion: pure rotation, circular motion, turns between two linear segments [10].

The complementarities and mutual influences of the several sensory modalities involved in navigation remain largely unknown. Different works showed that in addition to vision, an active motion of the body improves the perception of motion as well as the set-up and the transfer of spatial knowledge [4] [6] [13]. Harris et al. [8] have also shown that optic flow is not the dominant factor when determining the perception of a travelled distance. Although visual information can be used accurately when there are no competing cues, "it is dominated by any concurrent vestibular information" [8]. In another paper, Harris et al. [9] examined the contribution of visual and non-visual cues involved in the perception of self-motion. The perceived distance of self-motion can effectively be estimated from a passive visual flow. However, a passive physical motion turned out to be a particularly important cue: "not only does it evoke an exaggerated sensation of motion, but it also tends to dominate other cues" [9].

3. Apparatus

3.1. General Presentation

In our experiment, we have considered the situation of a passive visual navigation in which the participants do not have the control of their motion.

Figure 1 – Experimental Set-Up.

Participants were seated in front of a large projection screen (see Figure 1), and watched a visual flow corresponding to a displacement inside of a virtual environment. Participants were constrained to navigate on a pre-defined path, without having the possibility to change either the speed, the gaze's orientation or the direction of motion.

Participants held a haptic device with the right hand (see Figure 1). A haptic feedback was sometimes sent to them during visual navigation. The participants' responses were entered using a standard mouse – manipulated with the left hand (see Figure 1).

The following parts describe precisely both the visual stimulation and the haptic feedback that were used.

3.2. Visual Stimulation

The virtual navigation was an exploration of a virtual tunnel (see Figure 2). Participants navigated inside a tubular pipe with a circular section. The trajectory included one turn between two linear segments. The turn was defined on the horizontal plane. It created a certain deviation angle going either to the left or to the right.

The pipe was modelled using the 3DS MAX 5.1 software. The pipe model was made of one torus section and two cylinders. The interior of the components were uniformly mapped with a smooth stone-wall texture (see Figure 2).

Figure 2 – Passive Navigation inside a Virtual Tunnel.

The visual stimulation corresponding to the navigation inside the virtual tunnel was generated in real time with the Virtools 2.5 software. We defined the trajectory and orientation of a virtual camera exploring the interior of the pipe's model. The trajectory of the virtual camera was positioned at the centre of the tubular structure. The speed of the camera was kept constant. At the beginning of the navigation, the camera was positioned in the middle of the first cylinder. The visual navigation was stopped when the virtual camera reaches the middle of the second cylinder.

The virtual camera began its rotation slightly before the turn. This was meant to be consistent with navigation in real life. Indeed, a human anticipates turns and begins to turn the eyes and the head before the rest of the body [10].

The experimental set-up used a large projection screen of 2.5x2 meters with a 1280x1024 pixels resolution. The system used a Barco CRT projector for rear-projection. Participants were seated with their heads located at a distance of 2 meters from the screen. The participants' line of sight was aligned with the centre of the screen. The visual stimulation was displayed in monoscopic conditions with a frame rate of 100Hz. There was no source of light apart from the screen projection.

3.3. Haptic Feedback

The haptic interface used was the VIRTUOSE 35-40™ device from the Haption Company [1] (see Figure 3). Participants grasped the extremity of the interface – a handle – with the dominant hand. The forearm of the participants rested on the armrest of the seat, perpendicularly to the screen. In its neutral position, the participants' fist was aligned with the forearm.

Figure 3 – VIRTUOSE 35-40™.

During the navigation, the haptic feedback was sent at the moment of a turn. The haptic feedback consisted in rotating the handle around the vertical axis. The motion of the handle implied a rotation of the participants' fist by the same angle. Two types of haptic feedback were actually used:

- **Direct haptic feedback.** It consisted in rotating the handle by the same angle as the visual rotation and, after the visual turn, rotating back the handle to its neutral position. (if the visual navigation turned by 30° to the right, the handle was also turned by 30° to the right).

- **Indirect haptic feedback.** It consisted in rotating the handle by the same angular value as the visual rotation but in the opposite direction. (if the visual navigation turned by 30° to the right, the handle was thus turned by 30° to the left). After the visual turn, the handle was also rotated back to its neutral position.

During the visual turn, the rotation of the handle was controlled by the orientation of the virtual camera. The angular value of the handle's rotation corresponded exactly to the difference between the camera's current orientation and the camera's initial orientation (i.e. perpendicular to the screen), in the reference frame. The rotation speed of the handle was constant. After the visual turn, the handle was rotated back to its neutral position with a constant rotation speed. The profile of the handle's orientation during navigation is displayed on Figure 4.

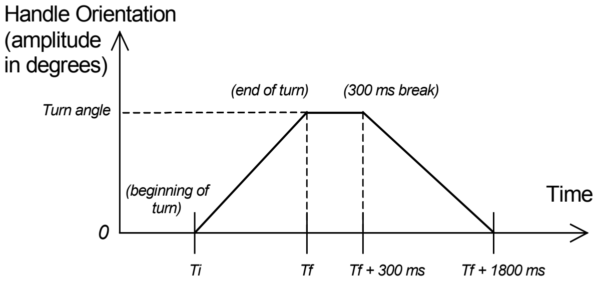

Figure 4 – Rotation of the Handle.

The naming of the two haptic feedback conditions (Direct vs. Indirect) was determined by the congruency between the visual rotation and the haptic one, during the visual turn. However, since the handle was always rotated back to its neutral position after the visual turn, participants experienced in each case (Direct or Indirect) both haptic rotations, but in different order.

The VIRTUOSE™ device is a 6 DOF force-feedback arm. The handle of the VIRTUOSE™ was forced to stay in the same position by using the force-feedback of the device. The orientation of the handle was also forced to remain aligned with the vertical axis. The unique possible motion of the handle remained the rotation around the vertical axis. The characteristics of the VIRTUOSE™ – notably its maximum and continuous torque values – prevented participants from moving the handle, stopping the handle's motion, or modifying the handle's orientation at any time. The force-feedback of the VIRTUOSE™ was controlled and sent back to the participants at a frequency of 1000Hz.

The experimental platform used 2 PC. One PC was dedicated to the graphic rendering, the motion of the virtual camera, and the data recording. The second PC was dedicated to the force-feedback computation and control. The two PC communicated via an Ethernet wire.

4. Experimental Procedure

4.1. Participants

Seven people took part in this experiment. They were all male and right-handed. They were aged between 18 and 25 and had no known perception disorders. The participants were all naïve to the purpose of the present investigation.

4.2. Procedure

Each trial consisted in one exploration phase followed by one reproduction phase. During the exploration phase, participants watched a passive visual navigation inside the virtual tunnel including one turn between two linear segments. A haptic feedback was sometimes sent during the turn. Participants were asked to always watch the screen and grasp the haptic interface with enough force so that the interface did not slide inside the hand. In the reproduction phase – immediately after the navigation – participants were asked to estimate the angle of the visual turn. The estimation was performed with a standard mouse, laying on a small table, that participants manipulated with the left hand. A top view of the virtual tunnel was displayed on the screen. When the participants clicked for the first time on the mouse, the left and right motions of the mouse were used to rotate the second segment of the tunnel. Participants were asked to reproduce the deviation angle and to validate the estimation with a second click. The participants could take all the time that they needed to answer. After the reproduction phase, the next trial was automatically launched.

No response feedback was provided. But at the beginning of the experiment, participants were proposed a learning phase. It included one block of trials including the 18 experimental conditions (see next part) – selected in a random order. The data collected during the learning phase were not taken into account for the data analysis. The full experiment lasted approximately 40 minutes. Participants could take a break between each block of 18 experimental conditions.

4.3. Experimental Conditions

Six values of turn's angle were chosen: +30, +40, +50, -30, -40 and -50 degrees. These values are a combination of two experimental factors: the angular amplitude (*30*, *40* and *50* degrees), and the turn's direction (*left* or *right*). Three conditions were possible concerning the haptic feedback: *Null* (no haptic feedback), *Direct* (presence of a direct haptic feedback), *Indirect* (presence of an indirect haptic feedback). The combination of the 3 angular amplitudes, the 2 possible directions of turn and the 3 haptic conditions implied a total amount of 3x2x3=18 conditions. Each condition was tested 4 times. Trials were grouped in blocks of 18 trials – each block containing the 18 experimental conditions. The order of the trials inside each block was randomised. A total of 4x18=72 trials were thus performed by each participant.

4.4. Recorded Data

At the end of each trial, two parameters were recorded: the estimation of the angle of the turn and the response latency (the time spent between the end of the visual navigation and the validation of the angle's estimation).

5. Results

5.1. Relative Angular Error

For one given angle (α*_expected*) and one participant's estimation (α*_measured*), it was possible to calculate the relative angular error (α*_error*) by using Equation 1:

$$\alpha\, error = \frac{|\alpha\ measured| - |\alpha\ \mathrm{exp}ected|}{|\alpha\ \mathrm{exp}ected|} \qquad (1)$$

Figure 5 shows the average values of the relative angular error made by the 7 participants when estimating the turn's angle according to the 3 haptic conditions – no haptic feedback (Null), direct haptic feedback (Direct), and indirect haptic feedback (Indirect).

Since the average values of the angular error are always negative on Figure 5, the angle of the turn was globally underestimated by participants in all conditions.

However, on average, the relative error of the 7 participants decreased in presence of a haptic feedback (Indirect or Direct), when compared with the no haptic condition (Null). This suggests that in presence of haptic feedback, the participants' under-estimation of the angle was reduced.

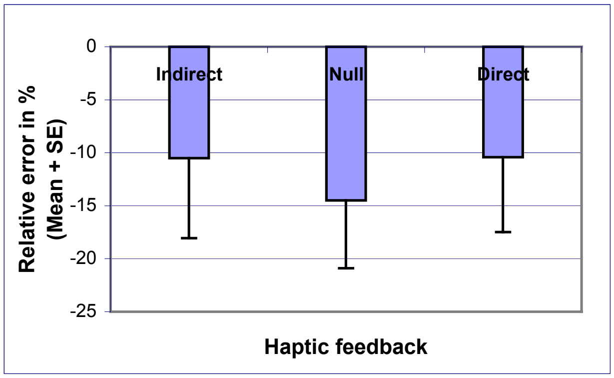

Figure 5 – Average Values of Relative Angular Error.

An analysis of variance (ANOVA) was performed on the relative error data. The within-participants factors included in the analysis were the angular value (30º, 40º and 50º), the turn's direction (left and right), and the haptic feedback condition (Indirect, Null and Direct).

ANOVA did not reveal a significant effect of the haptic condition on the relative error (F(2,10)=1.85; p=0.2). When observing the results of each participant separately, we noticed that the presence of haptic feedback did not influence all the participants similarly. It was possible to categorize descriptively the participants into 2 groups. The first group (n=3, "haptic") enclosed participants whose absolute relative errors was on average clearly decreased in presence of a haptic feedback. The second group enclosed the other participants (n=4, "no-haptic"). Figure 6 shows the combined effect of the group factor and the haptic feedback on the average relative error. The variability introduced by the different effects of haptic feedback among participants was probably responsible for the fact that the differences found with ANOVA between conditions – considering all the participants together – were not significant. Future experiments with a larger number of participants must thus be carried out to confirm our preliminary results.

There was no significant effect found for the angular value on the relative error. But there was a main significant effect of the turn's direction (left or right) on the relative error (F(1,6)=13.63; p<0.01). For a given angular amplitude, participants had a global tendency to more underestimate a left turn when compared with a right one. This effect is not observed in other related works [18]. It may be due to the asymmetry of our experimental apparatus. But future work is necessary to confirm this assumption.

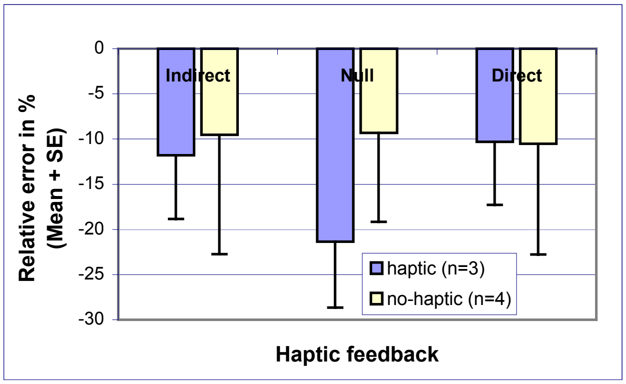

Figure 6 – Group Factor x Haptic Feedback Interaction on the Relative Error.

We also noticed several cases (6/504 cases, i.e. 1%) where the estimated angle was in the opposite direction of the visual turn. All these inversions happened in presence of an indirect haptic feedback. This suggests that indirect haptic feedback may sometimes distract or confuse people (6/168, i.e. 3,5% of all Indirect cases).

5.2. Response Latency

Figure 7 shows the average values of the response latency of the 7 participants when estimating the turn's angle according to the 3 haptic conditions.

On average, the response latency of the 7 participants increased in presence of a haptic feedback (Indirect or Direct), when compared with the no haptic condition (Null). Furthermore, the response latency with the indirect haptic feedback was globally longer than with the direct one.

This means that in presence of haptic feedback, participants had a global tendency to respond less quickly – and more specially with the indirect haptic feedback.

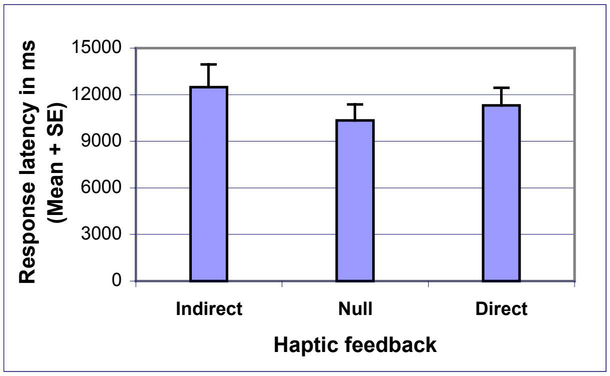

Figure 7 – Average Values of Response Latency.

This phenomenon was observed separately for each participant – and thus independently from the group factor ("haptic" or "no-haptic").

An ANOVA was performed on the response latency data. The within factors included in the analysis were the 3 angular values, the 2 turn's directions, and the 3 haptic conditions.

ANOVA showed a main significant effect of the haptic feedback on the response latency ($F(2,12)=9.11$; $p<0.004$). Contrasted comparisons showed that the response latency in Null condition (no haptic feedback) was significantly shorter than both in Direct condition ($F(1,6)=6.27$; $p<0.05$), and in Indirect condition ($F(1,6)=12.15$; $p<0.02$). The response latency was significantly shorter in Direct condition than in Indirect condition ($F(1,6)=5.96$; $p<0.05$).

There was no significant effect of the direction of the turn on the response latency. But a main effect of the turn's angular value on the response latency was found ($F(2,12)=14.78$; $p<0.001$). The response latency increased as a function of the angular value.

5.3. Final Questionnaire and Observations

At the end of the experiment, participants were asked to fill in a questionnaire.

A majority of participants (86% – 6 participants out of 7) found that haptic feedback can help estimate the turn's angle. Several participants (29% – 2/7) found that indirect haptic feedback may become confusing since it seems "inconsistent" with visual feedback.

This questionnaire indicates also that at least 43% of the participants (3/7) perceived a "real" sensation of motion of their body during the simulation. The sensation of self-motion was perceived during the visual turn and only when the direct haptic feedback was present.

Different strategies were set up by participants in order to improve their performances. Some "visual" and "haptic" strategies were observed. Participants generally combined and used more than one strategy. The "visual" strategy that was mainly observed consisted in estimating the time spent until the apparition of the turn's end. The faster the end of the turn appeared, the smaller their estimation of the turn's angle was. The "haptic" strategy that was mainly observed consisted in memorizing the rotation of the handle of the haptic interface. Furthermore, we noticed that some participants set up a recurrent behaviour in order to avoid the "confusing" influence of the indirect haptic feedback: the participants repeated orally the direction of the visual turn ("left" or "right") until the reproduction phase. Future work seems now necessary to measure the influence of these strategies on the performance of the participants.

6. Discussion

The reproduction of a perceived psychophysical variable – in our case: an angle – without response feedback or without knowing the range of the expected values inevitably leads to the classical "range effect" on the measured performances [18]. In our experiment, the expected range effect was indeed present since the turn's angles were globally underestimated in all conditions.

On the one hand, we found that for some participants the introduction of a haptic feedback during the visual turn improved the estimation of the turn's angle, clearly reducing their overall underestimation. On the other hand, for the other participants, the performance was on average the same with and without haptic feedback. Thus, we assume that haptic feedback globally improves the perception of self-motion during a virtual navigation containing a single turn. But future experiments – with a larger number of participants – must be carried out to confirm these preliminary results.

In contrast, when participants were provided with haptic feedback, the response latencies were longer. This suggests that combining haptics together with visual memory could improve the accuracy of estimation, but probably requires a longer processing time in order to integrate the two modalities into one consistent estimation of the turn's angle.

Interestingly, we found almost no difference in performance of estimation of the turn's angle between the direct haptic mode (rotation of the device in the same direction as the turn), and the indirect haptic mode (rotation of the device in the opposite direction). First, this could be due to the fact that both conditions proposed a good and identical information of angular amplitude. A second explanation is that there is a plausible cognitive interpretation for each mode – which could thus "naturally" improve the accuracy of the perception. In the direct mode, one can imagine that the haptic device reproduces the change of orientation of the point of view (i.e. it corresponds to a rotation of the camera in the virtual environment). In the indirect mode, one can imagine that the haptic device reproduces the change of orientation of the environment (i.e. it corresponds to a rotation of the virtual tunnel).

These two haptic "metaphors" can be related to two types of mental rotation – the "viewer's rotation" and the "object's rotation" – described in the literature [20] [21]. Many studies have indeed reported that performance in the spatial updating of an array of objects – a set of several oriented common objects – was significantly better after one had imagined the viewer's rotation than after one had imagined the object's rotation (see review by [20] [21]). The authors explain this discrepancy by the difficulty to perform cohesive separate rotation of each component of the array within a global intrinsic representation. Conversely, when the viewer moves, the relative reference frame is naturally and automatically updated. This explanation may stand for the difference in terms of response latencies that we found in our experiment between direct and indirect mode, which favours the direct mode. It is also consistent with the fact that a larger number of mistakes (inversions) were made with indirect haptic feedback.

However, another explanation for the superiority of "viewer's rotation" vs. "object's rotation" is that the mental transformation of images could require motor processes in the brain [19]. Indeed, a motor dual-task by means of a joystick succeeded in improving performance of mental rotation of the image when the two rotations are compatible [19]. Furthermore, the object's rotation nearly reached the viewer's rotation level of performance when the rotations included *haptic* information [21]. Including a haptic feedback and a motor process could thus improve the mental rotation, and remove the usual preference for the viewer mode over the object mode [19]. This hypothesis may explain why the same level of performance was observed in our experiment with direct and indirect haptic feedback. Both haptic modes included similar (but opposite) haptic information and motor processes.

Taken together, our results suggest that haptic feedback could contribute to the process of path integration involved when memorising a trajectory. Indeed, memorising a trajectory is a multisensory process which could be improved – at low or high level – by the presence of more information on the haptic mode.

7. Conclusion

This paper is a preliminary study of the influence of haptic feedback on the perception of self-motion in virtual reality. An experiment was conducted in which a simple haptic feedback was proposed to substitute for the sensations of self-motion that are absent in virtual environments – mainly proprioceptive and vestibular information. This haptic feedback was added to a passive visual navigation.

In presence of haptic feedback, the response latencies were longer. Thus, it probably requires a longer processing time to integrate two modalities (visual and haptic) into one consistent estimation. However, the haptic feedback globally seemed to improve both quantitatively and qualitatively the perception of self-motion. On average, it reduced the participants' under-estimation of the angles that the turns made in the visual navigation.

These results suggest that VR applications where navigation plays a key role could be improved by the presence of an appropriate haptic feedback. The foreseen applications of this work are for example: video games, driving simulators, mission preparations, virtual visits, but also mobility training and guidance of blind people.

Future work. First, this preliminary study must be followed by a similar experiment with more subjects (n>20). This future experiment could take into account the range effect by including an appropriate response feedback for the participants' calibration. Second, the haptic feedback proposed in this paper could be studied when the visual rotations are made around the pitch axis. In this case, an asymmetrical effect (up vs. down) was reported concerning the estimation of the turns' angles [18]. Can haptic feedback help compensate for this asymmetrical effect? Third, the addition of haptic feedback must be tested with more complex trajectories such as virtual labyrinths [13]. Fourth, other haptic feedback could be implemented. For example, force or torque feedback could be used to simulate the notion of acceleration in a homogenous way.

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