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Technical Section

Influence of the size of the field of view on motion perception

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ABSTRACT

Efficient navigation requires a good representation of body position/orientation in the environment and an accurate updating of this representation when the body–environment relationship changes. Such updating is based on the ability to correctly estimate the speed and amplitude of body displacements. Because navigation in virtual worlds often relies on the sole visual information, we investigated to which extent the size of the field of view (FoV) affects two basic aspects of motion perception: (i) the perceived amplitude of rotations about the body vertical axis (Experiment 1) and (ii) the perceived speed of forward translations (Experiment 2).

Concerning the perception of rotation amplitude, we found that visual flow information gives rise to inaccurate and very variable estimations, with a systematic underestimation of rotations larger than 30°. We also found that the accuracy of the estimations does not depend on the size of the FoV and that horizontal FoVs larger than 30° do not improve the performance. Concerning speed perception, central FoVs smaller than 60° gave rise to an underestimation of the visual speed. On the other hand, occluding the central area leaving only peripheral visual information available induced a systematic overestimation of visual speed, even when only the central 10° of vision was occluded. Taken together, these results suggest that large FoVs are not required to estimate the amplitude of visual rotations about the vertical axis of the body, whereas central FoVs of at least 60° are advisable when speed perception relies on visual flow information.

1. Introduction

When moving around an environment, different sensory channels – i.e., vision, proprioception or the vestibular system – provide us with congruent information about the amplitude, speed and acceleration of our displacements [1–8]. This information is used to permanently update the representation of visual space in order to navigate efficiently in the surrounding world. When navigating in virtual worlds, however, vision often constitutes the only available sensory input. In line with this, understanding how visual information is used to estimate the amplitude of the relative displacements between the body and its surroundings has potential applications in the design of virtual environments.

As opposed to the real world, most of the displays used in virtual reality have a restricted field of view (FoV). This is for instance the case with head-mounted displays (HMDs), for which the field of view lies mostly within the range 30–60° (as illustrated in Fig. 1). Yet, several studies suggested that peripheral vision is critical for motion perception, showing that the size of the FoV affects navigation abilities [9,10], postural control [11–13], speed perception [14,15] and the sensation of self-motion induced by a moving visual stimulus [16–20]. For instance, Turano et al. [10] have shown that peripheral visual information is important for establishing and updating an accurate representation of the spatial structure of the environment. Similarly, Alfano and Michel [9] have shown that the quality of the cognitive representation of the visual space decreases when the FoV decreases. Concerning postural control, spontaneous standing sway increases without peripheral vision but remains unaffected by the occlusion of central vision [11,12]. Finally, a large literature devoted to the study of vection, i.e., the illusion of self-motion induced by a moving visual stimulus, suggests that peripheral vision plays a dominant role in evoking such illusion [16–18].

In the present paper, we investigated to which extent the size of the FoV affects two basic aspects of motion perception, i.e., the perceived amplitude of rotations about the body vertical axis (Experiment 1) and the perceived speed of forward translations (Experiment 2). Within the visual modality, two different kinds of cues can be used to estimate the relative displacements between the body and the environment. First, the fixed structure of the visual scene provides static cues or landmarks. Motion amplitude can be estimated by computing the changes in the relative position/orientation of the body with respect to these landmarks [6,21]. Second, the relative motion between the observer and the visual scene generates a visual flow on the retina, which can be

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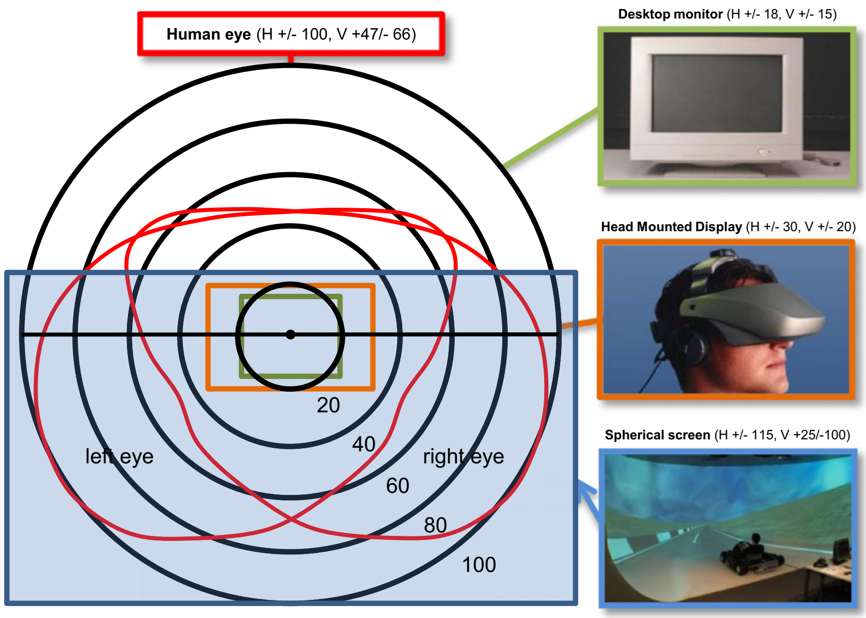

Fig. 1. Field of view in degrees of different setups compared to the human field of view (drawn after a graphic from CHI Data Visualization 'http://www-users.cs.umn.edu/~echi/tutorial/perception2000').

used to update body position/orientation in the environment [3,7,8]. Our work specifically focused on the contribution of the visual flow to motion perception. Therefore, in both experiments, we used a visual scene devoid of any landmark, and the participants were required to maintain central fixation during visual motion so that they could not use eye movements to code the amplitude or the speed of the scene displacement.

2. Experiment 1

2.1. Introduction

In this experiment, we tested how visual flow information can be used to update the representation of body orientation in the environment, and whether a limited FoV, as found in most virtual reality applications, degrades the performance as compared to a full FoV. We used a spatial updating task in which the subjects had to take into account rotations of the visual scene about the body vertical axis to update the egocentric position of a memorized target. In some conditions, vertical masks were used to restrict the size of the horizontal FoV to 30° and 60°.

2.2. Methods

2.2.1. Participants

Ten participants (aged 21–35, mean = 24.5) took part in the experiment. None of them had a history of sensorimotor disorder, and all had normal or corrected-to-normal vision. All participants gave their informed consent before taking part in the experiment, which was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

2.2.2. Experimental setup

The subjects were seated in a darkened room, centrally located within a quarter sphere screen (Fig. 2).

The height of the chair was adjusted for each subject so that the head was at the 'origin' of the screen, i.e., the point from which the geometry of the virtual scene is correct. A wheel-controlled potentiometer with a pointer and two buttons was fixed 25 cm in front of the subject and used to launch the trials and give the responses. The visual scene consisted of white dots with limited lifetime randomly generated in a 3D hollow cylinder centered on the eyes' position (Fig. 3a).

Fig. 2. Panoramic screen, 230 × 125° of field of view, including floor.

In the full FoV condition, this random dots pattern covered the whole screen (Fig. 4a). In the 30° and 60° FoV conditions (Fig. 4b and c), software-implemented blinders (background-colored) were used to limit the horizontal field of view symmetrically on both sides of the central fixation cross (Fig. 3b).

When rotated, this random dots pattern induced a visual flow corresponding to a self-rotation around the vertical axis of the subject. The central fixation consisted of a red cross sustaining 1.5° of visual angle and the target was a red dot of 1° of visual angle.

2.2.3. Procedure

The time course of a trial is represented in Fig. 5. At the beginning of each trial, the fixation cross was presented directly in front of the participants at eye level. Subjects were instructed to maintain fixation for as long as the cross was displayed. One second later, the dots pattern was also presented and remained stationary. After 1 s, the target was presented for 2 s, 5° left from the central fixation cross. The dots pattern could be rotated and the subjects had to update the memorized position of the target according to the perceived rotation (i.e., direction and amplitude) of the pattern 125 ms after target extinction. The fixation cross forced the subjects to rely exclusively on the visual flow to update the position of the target. In particular, it prevented the subjects from tracking the dots during the rotation of the pattern, which would have enabled them to use eye movements to code the amplitude of the rotation. The rotations had a raised-cosine velocity profile and lasted between 800 and 2750 ms, depending on the amplitude and peak acceleration. The fixation cross and the dots pattern were switched off 3 s after target extinction. The subjects could then give their response, using the pointer to indicate the position at which the target would be if it moved with the dots pattern. More specifically, they had to first orient the pointer towards the estimated position of the target, then press the left button to get visual feedback about the pointed position and fine-tune the pointing and finally validate the response by pressing the right button. This pointing procedure was used to limit the response bias that was likely to occur if using an adjustment procedure. During this pointing stage, the subjects were free to move their eyes and head.

2.2.4. Conditions, blocks and duration

The experiment used three independent variables: (i) the horizontal field of view, or visual angle sustained horizontally by the dots pattern (three levels: 30°, 60° and 230°, all horizontally centered on the central fixation cross); (ii) the rotation amplitude of the dots pattern (nine levels: clockwise and counterclockwise rotations with four different amplitudes in each direction (15°, 30°, 45° and 60°) plus a control condition in which the pattern remained stationary) and (iii) the peak acceleration of the rotations (two levels: $50°/s^2$ and $150°/s^2$). The experiment therefore consisted of 54 different conditions. Each subject performed five repetitions of each condition for a total of 270 randomly ordered trials, which were split into three blocks of 90 trials each. Before running the experimental blocks, each subject first conducted two training blocks of 20 trials each. In the first training block, the target remained on the screen for the whole duration of the trials, rotating with the pattern. This block notably allowed the subjects to have a better representation of the rotations of the target, and to familiarize themselves with the pointing device. The second training block was identical to the experimental blocks, i.e., the target was extinguished before the rotations of the pattern. Each experimental block lasted about 30 min with a 5 min break between two successive blocks. In total, the experiment lasted about 2 h, which included 20 min devoted to instructing and training the subjects at the beginning.

2.2.5. Data analysis and statistics

Pointing errors were computed by comparing the pointing responses with the actual target position after rotation. Underestimations of the amplitude of the target (dots pattern) rotation were assigned negative values and overestimations positive values. The size and the variability of the signed pointing errors were entered in two separate 3∗9∗2 [FoV (30, 60 and 230)∗rotation amplitude (ccw60, ccw45, ccw30, ccw15, 0, cw15, cw30, cw45 and cw60)∗peak acceleration (50 and 150)] repeated measures analyses of variance (ANOVA). Post hoc comparisons using Newman–Keuls tests ($p<0.05$) were conducted when necessary.

2.3. Results

For the control trials, the pointing responses were very accurate and little variable, the average pointing error being

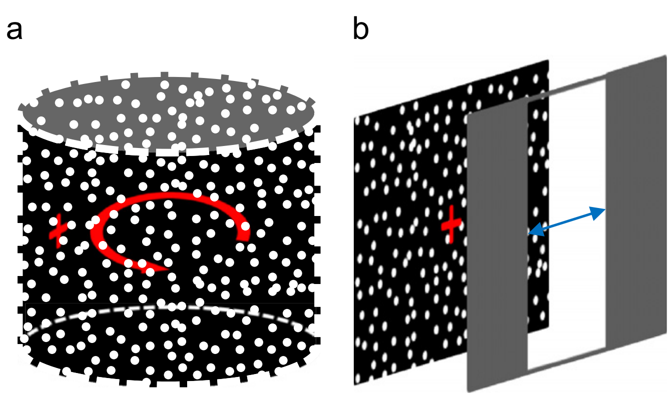

Fig. 3. Representation of the visual scene: the arrow indicates the rotations about the vertical axis in a cylindrical volume of random dots (a) and software-implemented blinders limit symmetrically the horizontal FoV (b).

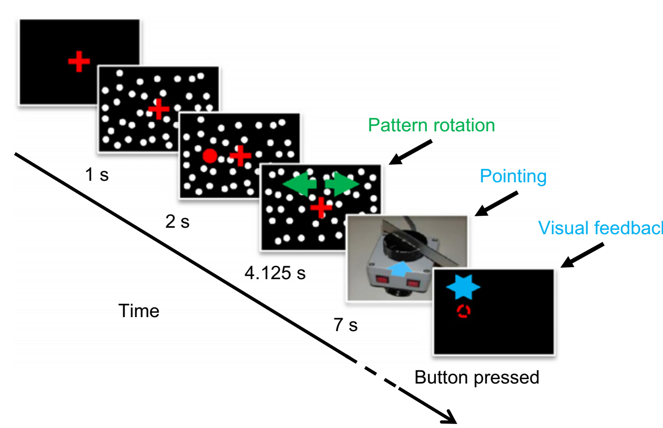

Fig. 5. Trial time course.

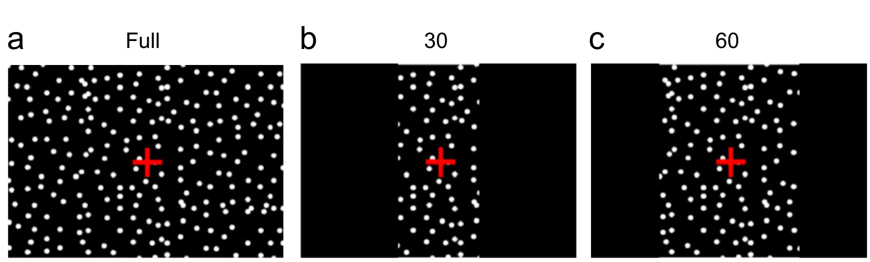

Fig. 4. Experimental conditions: full FoV (a); horizontal FoV limited to 30° (b) and 60° (c).

$0.1 \pm 1.7^{\circ}$. Concerning the trials with rotation, the subjects were able to perform the task and estimate the rotation amplitude of the dots pattern. As shown in Fig. 6, the average perceived amplitude of the rotations correlates pretty well with the actual amplitude.

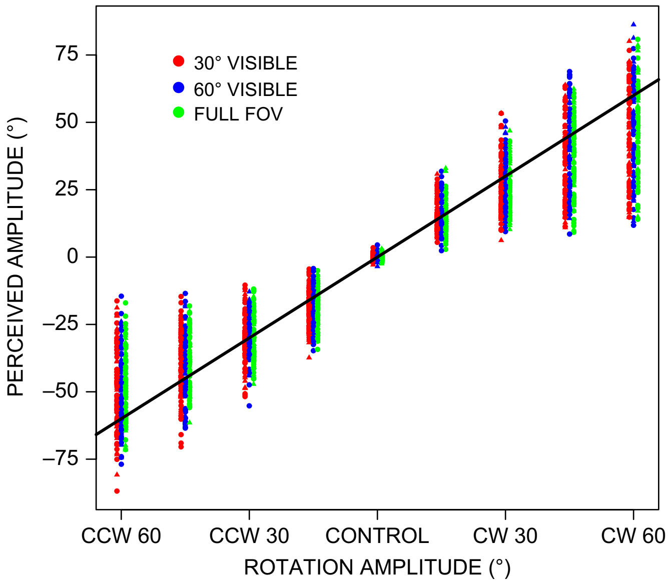

Fig. 6. Perceived rotation of the visual scene as a function of the actual rotation. All single responses are plotted. The three FoV conditions are color-coded. The black line corresponds to $Y = X$.

However, a closer look at the pointing errors indicates that if the amplitude of the small rotations (15° and 30°) was on average relatively accurately perceived, the amplitude of larger rotations was systematically underestimated, the underestimation increases with the amplitude of the rotations (Fig. 7).

In line with this, the ANOVA on the size of the signed pointing errors revealed a main effect of the rotation amplitude ($F8, 72 = 12.01$; $p < 0.001$). The post hoc tests, however, failed to indicate any significant difference between the different levels, probably because of the large variability of the pointing responses. Neither the size of the field of view nor the peak acceleration of the rotations had a significant influence on the size of the signed pointing errors.

As shown in Fig. 7, the variability of the responses increased with the amplitude of the rotations. This was confirmed by the ANOVA ($F8, 72 = 56.64$; $p < 0.001$). Notably, the post hoc tests indicated that the variability of the responses was significantly smaller when no rotation occurred (control) than for all rotation amplitudes but 15° clockwise. Also, the variability of the responses for the 15° rotations (clockwise and counterclockwise) was significantly smaller than for the largest two rotation amplitudes (45° and 60° in either direction). The size of the field of view also had a significant effect on the variability of the responses ($F2, 18 = 4.36$; $p < 0.05$), the variability tending to decrease as the field of view augmented (post hoc tests non significant, though).

2.4. Discussion

The results of the present experiment show that (i) visual flow alone can be used to estimate the amplitude of rotations of the

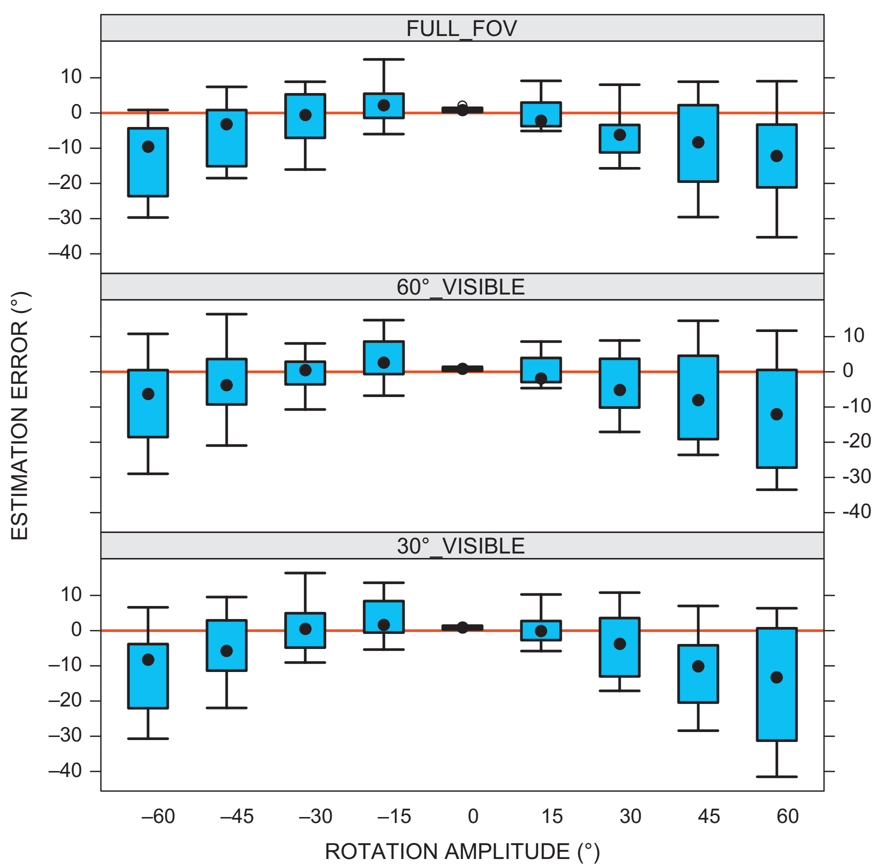

Fig. 7. Estimation error as a function of the FoV and the rotation amplitude. Each box summarizes the distribution of responses of all subjects. The central dot, the box and the whiskers correspond to the median, the 50% and the 99% confidence interval of the responses, respectively. Data points located below and above the red line correspond to an underestimation and an overestimation of the rotation amplitude, respectively.

environment relative to the body, (ii) these estimates are quite variable and this variability augments with the amplitude of the rotations, (iii) beyond 30° of visual scene rotation, the amplitude is systematically underestimated, scaling with increased visual scene rotation, (iv) increasing the size of the horizontal FoV (30° being the baseline) does not affect the average performance but slightly reduces the variability of the responses and (v) in the range 50–150°/s^2 of peak acceleration, the perceived amplitude of the rotations is unaffected by the velocity profile of the rotations.

Previous studies have investigated a human's ability to use visual information to update the representation of the visual space when the orientation of the body changes with respect to the environment [3,5,7,8]. These studies report that the visual flow alone does not allow for an accurate updating of the representation of visual space. Although the paradigm and stimuli used in the present experiment differ from those on which these previous studies were based, our results confirm these findings. Therefore, when only visual information is available for navigating in virtual worlds, landmarks should probably be provided. For the large rotations of the visual scene, the subjects systematically underestimated the amplitude of the rotation. Similar underestimations of the amplitude of the stimulation have already been reported for visual [5] as well as vestibular [2] rotations about the body vertical axis. Bakker et al. [5] suggested that such a tendency to stop before a target is reached might have been brought about by evolution to stop us early from dangerous collisions with objects or from falling into pits. They interpret the increasingly larger undershoot errors as a way to maintain an adequate safety margin when the confidence in the accuracy of the path integration decreases. An alternative explanation is that these underestimations merely reflect a range effect [22], i.e., a response bias towards the middle of the range of the possible responses that is commonly observed in subjective assessments. In contrast to other studies that have reported an effect of horizontal FoV size on motion perception [14–20], we found only a slight reduction of response variability when the size of the FoV was increased, and absolutely no effect on average performance. Our results therefore suggest that when only visual flow information is available, having more than 30° of horizontal field of view may not provide enough useful information to update the internal representation of space. We are currently employing additional experiments to determine the influence of the vertical field of view.

3. Experiment 2

3.1. Introduction

During translations along the antero-posterior axis, the angular velocity of the visual flow on the retina varies with the retinal eccentricity of the stimulus. In this experiment we tested how the perceived speed of translation is affected by the portion of the retina that is stimulated when only limited regions of the FoV are visible. Subjects were presented with visual translations at constant speed through a volume of random dots. The perceived speed was compared between different FoV conditions, masks of different sizes being used to occlude either central or peripheral areas of the FoV.

3.2. Methods

3.2.1. Participants

Ten participants took part to the experiment. None of these participants was included in the first experiment. All had normal or corrected-to-normal vision. They were paid and naïve as to the purpose of the experiment. All participants gave their informed consent before taking part in the experiment.

3.2.2. Experimental setup

As for Experiment 1, the subjects were located at the center of the panoramic screen and the eye height of each participant was adjusted to 1.7 m in order to avoid geometrical distortions induced by the curved display. The visual stimuli consisted of random patterns of white dots generated as point sprites (2×2 pixels) randomly located within a large virtual cube (Fig. 8a). Soft-edge disc-shaped transparent masks were implemented in the visual scene in order to manipulate the extent of the visible area on the screen (Fig. 8b).

In the full FoV condition, the dots were visible on the whole screen (Fig. 9a). In the central FoV conditions, the random dots pattern was displayed only within circular transparent masks of 10°, 20°, 40° and 60° centered on the fixation cross (Fig. 9b). In the peripheral FoV conditions, the disks covered the dots within the central portions of the screen (10°, 20°, 40° and 60°), leaving only the outer region visible (Fig. 9c).

The fixation cross was visible for the whole duration of the trials. The movement of a virtual camera through the dots induced a radial visual flow corresponding to a self-translation along the antero-posterior axis of the subject (Fig. 8a). The subjects gave their responses using a joystick with two buttons.

3.2.3. Procedure

The experiment was a two-interval forced-choice (2-IFC) task. For each trial, participants were successively presented with two stimuli (i.e., standard and comparison stimulus) moving at constant speed and instructed to indicate in which interval the stimulus was faster. The interval time course is presented in Fig. 10.

At the beginning of each interval, a fixation cross appeared on a dark background in front of the participant at eye level. Participants were instructed to gaze at the cross and maintain the fixation until the end of the trial. 500 ms later, the first stimulus was presented, i.e., a random dot pattern moving towards the subject appeared. The moving stimulus was presented for 700 ms which included a 100 ms fade-in phase at the beginning and a 100 ms fade-out phase at the end. The second stimulus was presented 500 ms after the end of the first stimulus and had the same temporal structure as the first one. The fixation cross disappeared at the end of the second stimulus and the participants could give their response.

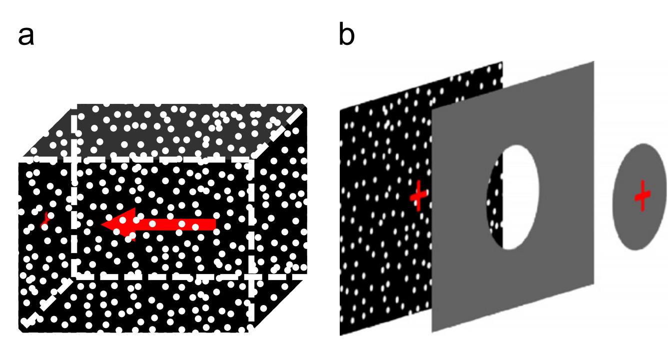

Fig. 8. Representation of the visual scene: the arrow indicates the translation along the antero-posterior axis in a volume of random dots (a) and software-implemented disc-shaped masks limit the extent of the visible area on the screen (b).

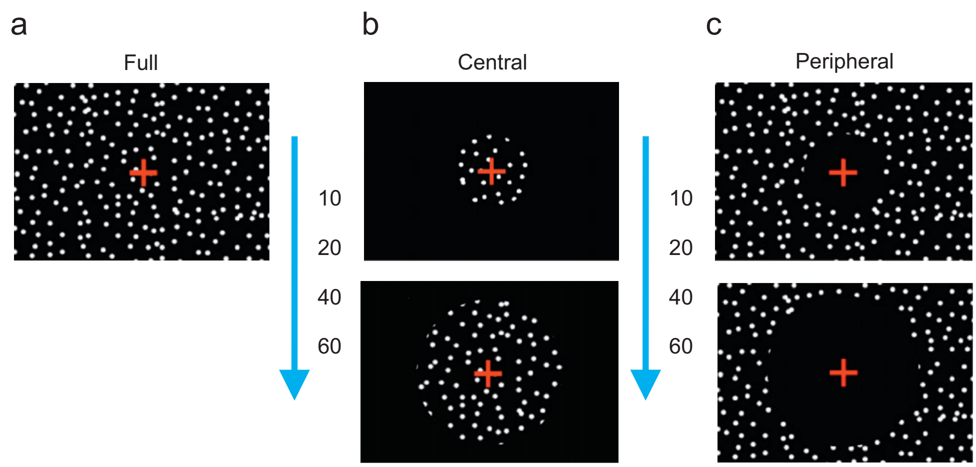

Fig. 9. Experimental conditions: full FoV (a); central visible, from 10° (top) to 60° (bottom) (b) and peripheral visible, with central region occluded from 10° (top) to 60° (bottom) (c).

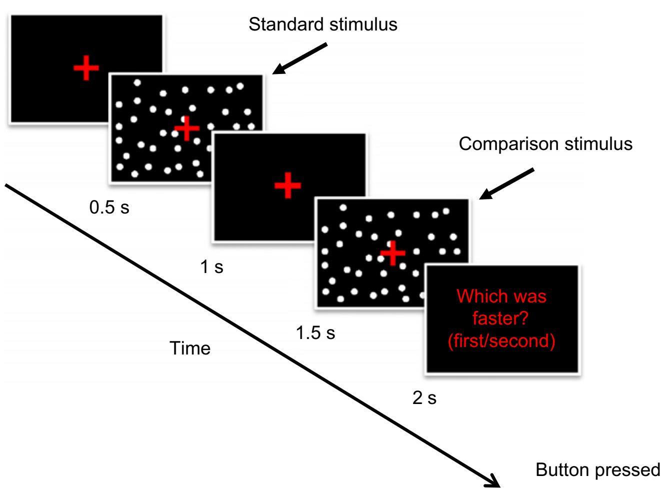

Fig. 10. Trial time course.

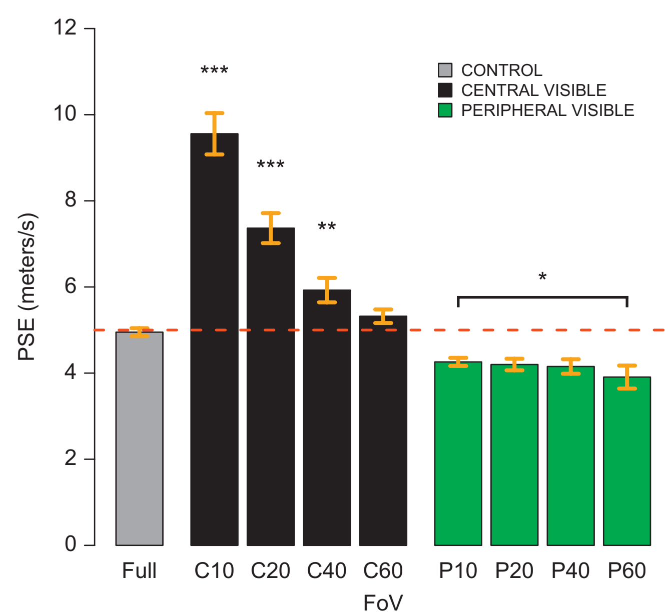

Fig. 11. PSE mean values as a function of the FoV. The red dashed line corresponds to the actual speed of the standard stimulus.

3.2.4. Conditions, blocks and duration

The speed of the standard stimulus was always 5 m/s with full FoV. The speed of the comparison stimulus varied from one trial to the other, being determined for each trial by a Bayesian adaptive method [23]. This method defines the test speed of the following trial by optimizing the information gained with the current response, and taking into account the previous tested values and subject responses. The optimization algorithm takes as initial parameters the estimated ranges of the mean speed, the standard deviation and the tested speeds, which were determined in a pilot experiment. Also, nine different FoVs were used for the comparison stimulus, constituting the nine experimental conditions: Full (control condition), Central visible 10, Central visible 20, Central visible 40, Central visible 60, Peripheral visible 10, Peripheral visible 20, Peripheral visible 40 and Peripheral visible 60. The Bayesian adaptive method was used independently for the different conditions and 80 trials were performed in each condition, for a total of 720 trials. The trials were presented in random order in nine blocks of 40 trials each. For each trial, the order of presentation between the standard and the comparison stimulus was randomly selected. Small breaks were allowed between two successive blocks. The total duration of the experiment was less than 2 h, which included instructions and training.

3.2.5. Data analysis and statistics

For each condition, the perceived speed was measured as the Point of Subjective Equality (PSE), i.e., the speed at which the comparison stimulus was perceived to move as fast as the standard stimulus. In other words, a PSE higher than the actual speed of the standard stimulus indicates that the comparison stimulus was perceived as slower than the standard stimulus, whereas a PSE lower than the speed of the standard stimulus indicates that the comparison stimulus was perceived as faster than the standard stimulus. The variability of the responses was measured as the Just Noticeable Difference (JND), which indicates the smallest detectable difference between the speed of the comparison stimulus and the speed of the standard stimulus. This measure corresponds to the standard deviation of the PSE for each condition. A one-factor nine-levels [FoV (full; 10°, 20°, 40° and 60° central; 10°, 20°, 40° and 60° peripheral)] repeated-measures analysis of variance (ANOVA) was conducted on the PSE and JND values. When necessary, post hoc tests using the Newman–Keuls

Table 1
Significance (p) of the pairwise comparisons between the PSEs for the different FoVs.

	Full	C10	C20	C40	C60	P10	P20	P40
C10	0.000124							
C20	0.000150	0.000115						
C40	0.002521	0.000111	0.000140					
C60	0.308500	0.000150	0.000111	0.016620				
P10	0.027026	0.000127	0.000124	0.000150	0.004545			
P20	0.021912	0.000126	0.000127	0.000124	0.002075	0.643516		
P40	0.037548	0.000123	0.000126	0.000128	0.003080	0.878109	0.983124	
P60	0.018315	0.000136	0.000123	0.000126	0.001133	0.796660	0.894324	0.669094

adjustment method for multiple comparisons ($p<0.05$) were performed.

3.3. Results

For the control condition (i.e., comparison stimulus with full FoV), the responses of the participants were highly accurate, the average PSE being 4.98 ± 0.15 m/s. This result indicates that participant were perfectly able to perform the task and estimate the speed of translation of the dots pattern.

Fig. 11 shows the PSE mean values for the nine FoV conditions. The ANOVA on the PSE indicated a significant effect of the FoV ($F8, 72 = 77.78$; $p<0.001$). With central FoVs smaller than 60° (i.e., peripheral vision occluded), the visual speed was systematically underestimated, the bias being inversely proportional to the size of the FoV. In contrast, when the central region was occluded and visual flow only presented peripherally, the speed was systematically overestimated. This overestimation was observed even when only 10° of central FoV were occluded. The significance values (p) of the post hoc tests are presented in Table 1.

The JND values are shown in Fig. 12. The ANOVA revealed no effect in the variability of the responses ($p>0.05$), indicating that the sensitivity of the participants in estimating the visual speed was comparable in all FoV conditions.

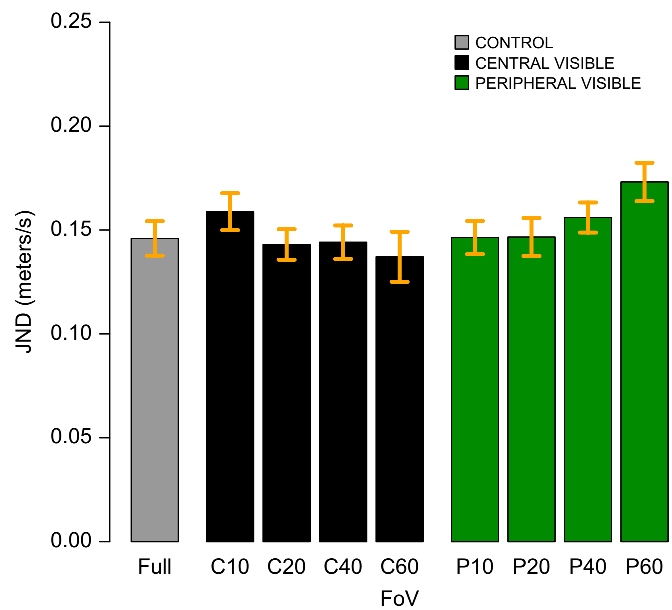

Fig. 12. JND mean values for the different FoVs.

3.4. Discussion

The results of the present experiment show that (i) visual flow alone can be used to estimate the speed of forward translation during self-motion through the environment, (ii) when the FoV is smaller than 60° the visual speed is underestimated, the bias being inversely proportional to the size of the visible area, (iii) when the visual flow is presented only peripherally, the perceived speed of translation is systematically overestimated, even when only 10° of central FoV are occluded and (iv) the variability of the responses is not affected by the FoV.

Previous works reported speed underestimations with a reduced FoV. For instance, Osaka evidenced a decrease in the perceived driving speed as the FoV was systematically reduced from 55° to 3° [14]. In a bicycling simulation, the perceived cycling speed was underestimated with a FoV smaller than 73°, and was slightly overestimated with FoVs of 103° and larger [24]. More recently, Segawa et al. [25] reported that the perceived speed of translation through a simulated tunnel decreases as the visible area was limited to 5%. Also, in simulated walking studies, the findings are consistent with the present results. Banton et al. [26] reported that a 4.8 km/h walking speed was perceived to be about 50% slower than normal during straight-ahead gaze. Pretto et al. [15] found similar results in a driving simulation with reduced visibility conditions. In their experiment, the perceived speed was higher when the central region of the FoV was occluded and lower when the peripheral region of the FoV was occluded. They formulated the hypothesis that during forward self-motion with a restricted FoV, the availability of low angular velocities in the central area of the FoV directly decreases the estimated speed. The results of the present experiment with more controlled visual stimuli tend to confirm this hypothesis. Indeed, using 'pure optic flow' stimuli, we tested directly whether the difference in angular velocities produces a systematic bias in speed estimation. Our results clearly show that the perceived speed during forward motion is strongly affected by the FoV, restricted central FoVs (i.e., less than 60°) leading to speed underestimation and occlusion of the central area of the FoV inducing speed overestimation.

4. Conclusions

The extent of the FoV and the presence of visual cues at the peripheral regions are important design questions to be considered for the visual rendering of virtual environments. The two experiments presented here show that the size of the FoV affects differently the perception of the amplitude of rotations about the vertical body axis and the perception of the speed of forward translations. In particular, whereas the size of the FoV did not affect at all the perception of yaw-axis rotations (Experiment 1), the speed of forward translations was underestimated with FoVs smaller than 60° (Experiment 2).

The results of the first experiment suggest that for applications in which the user has to orient himself accurately in the environment (e.g., virtual navigation), optic flow alone only gives rise to poor performance. Indeed, we observed a strong tendency to underestimate the amplitude of visual rotations, the amplitude of the underestimation increases with the amplitude of the rotation. In line with this, landmarks should probably be provided if the amplitude of the rotations has to be accurately perceived. However, for such applications, a horizontal FoV of 30° seems sufficient, which implies that HMD can probably be used. That was not tested here, and some further tests in that direction should be performed since there are some known differences between screens and HMDs, notably for distance perception [26,27].

The results of the second experiment show that optic flow information can reliably be used for speed estimation (i.e., low variability of the estimates), but that the size of the FoV plays a critical role in the performance. In particular, the visual speed is underestimated with central FoVs smaller than 60° and over-estimated if the central 10° of the FoV (or more) is occluded. This suggests that for application in which speed estimation is critical, as for instance driving or flying simulators, the user should be provided with a central FoV larger than 40°, ideally of 60°. However, FoVs larger than 60° are probably not necessary for speed estimation since we failed to observe any significant difference between a FoV of 60° and a full FoV (which is confirmed by other results with similar stimuli and not presented here).

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