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Between Desktop and Head Immersion:

Functional Visual Field During Vehicle Control and Navigation in Virtual Environments

Abstract

The effects of available visual information in the periphery (enlargement of the functional visual field) on performance in navigation were evaluated in an experimental setup searching for a "compromise" between desktop and head-immersion situations. A Fixed Vision condition (fixed display) and two Mobile Vision conditions (head-tracking with a visual field of variable width) were compared in six virtual environments of different complexity and in four successive sessions. First, a global improvement in performance throughout the sessions revealed a gradual integration of the properties of the simulation device. Second, performance was higher in the Mobile Vision conditions, as shown by the smoothness of the subjects' paths (sharp curves could be negotiated without stopping), indicating the importance of a wide functional visual field. In conclusion, the need to design realistic and functionaly efficient human-machine interfaces for navigation is discussed.

1 Introduction

The definition of the content and format of visuospatial information available to the operator is one of the major human factors in remote-controlled situations. In such situations, although the vehicle under control is out of the operator's direct sight, visual control remains the dominant mode in most cases. Indeed, ''direct'' visual perception is replaced by images produced by video cameras on-board the vehicle (Péruch, Mestre, Pailhous, & Savoyant, 1993). The choices made concerning the information given to the operator necessarily modify the specific conditions under which control of the vehicle's displacement is achieved. These modifications, as well as the difficulties they create for the operator, raise many questions, including the nature and perceptual bases of navigation. With respect to the perception of the displacement of the vehicle, the static operator lacks kinesthetic and vestibular information which is usually associated with self-motion. In such purely visual conditions, the vehicle's orientation and movement control are difficult for many reasons. First, part of the difficulties arise from the fact that depth and distance perception are distorted by the video interface. Second, problems may result from missing or partial ground perception, or from the fact that part of the vehicle cannot be perceived on the video terminal (Mestre, Cavallo, & Péruch, 1986;

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Slater & Usoh, 1993). Third, the video camera itself can introduce problems due to optical deformations and a limited visual field, in particular, missing peripheral vision (Hightower, Spain, & Bowles, 1987; Miller & McGovern, 1988; and Padmos & van Erp, 1996).

In spite of many drawbacks that can be considered as being mainly due to the present state of the art, virtual environments (VEs) are increasingly used as an experimental tool for studying human spatial behavior (Péruch, Vercher, & Gauthier, 1995; Péruch, May, & Wartenberg, 1997; and Wilson, 1997). Two of their major strengths are the possibility they create to disentangle one sensory modality from others, and to make measurements all along environment- and time-extended navigations. For instance, they may allow a systematic investigation of the visual aspects of navigation. With VEs, spatial information is generally presented in two ways: desktop or head-immersive situations. In the former, the observer views the virtual environment on a computer screen, while in the latter the observer wears a helmet in which the scene is displayed. These two modes of presentation differ in several respects: in desktop situations the direction of gaze is usually linked to the direction of displacement (the translations and rotations being produced, for example, via a joystick). In head-immersion situations, the direction of gaze is linked to head movements. In other words, vestibular and kinaesthetic information, which could be an important factor with respect to the acquisition of spatial knowledge, is available in head-immersion situations only. Finally, although image quality is generally poorer and the visual field smaller in head-immersion than in desktop situations, the scene occupies a wider functional visual angle in the former, thanks to head movements. Consequently, comparisons between head-immersion and desktop situations reveal contradictory results with respect to the superiority of one device over the other. (See, for example, Arthur, Hancock, & Chrysler, 1997; Foreman & Wilson, 1996; Henry, 1992; Ruddle, Randall, Payne, & Jones, 1996.)

The size of the observer's instantaneous field of view (FOV) can be an important factor for at least two reasons. First, it has been found that FOV affects the accuracy of perceiving spatial relations in pictures: errors are generally found to be larger with smaller FOVs (Bengston, Stergios, Ward, & Jester, 1980; Neale, 1996; Psotka, Lewis, & King, in press). Second, some work with moving observers in real environments has revealed the influence of FOV on the acquisition of spatial knowledge, presumably as a function of the number of spatial relations perceivable at a time (Alfano & Michel, 1990; and Rieser, Hill, Talor, Rosen, & Bradfield, 1992). FOV could also influence spatial knowledge acquisition as a function of the degree of participation of peripheral visual mechanisms: the larger the observer's FOV, the larger the degree of participation of peripheral visual mechanisms (Johansson & Börjesson, 1989; and Warren, Mestre, Blackwell, & Morris, 1991). Moreover, the use of VEs allows an important distinction to be made between the observer's FOV and the geometric field of view (FOVg), which corresponds to the visual angle of the model subtended at the computer's virtual eye (Sedgwick, 1991). Concerning the influence of FOVg in perspective displays, it has been shown that a FOVg greater than the observer's FOV can compensate for errors in direction estimates that are typically observed in perspective displays when FOVg matches the observer's FOV (McGreevy & Ellis, 1986; Grunwald, Ellis, & Smith, 1988). However, in a triangle completion task performed in VEs, Péruch, May, and Wartenberg (1997) found no FOVg effect even when it was larger than the FOV (60 deg. versus 80 deg.). Psotka et al. (in press) explain the distortions caused by limited FOV in perspective displays by assuming that the observer always cognitively interprets a scene on a display as viewed under the full 180 deg. FOV of the human visual system. In summary, it appears that FOV-versus-FOVg variations give rise to different interpretations, and seem to depend on the experimental situation.

The present study was aimed at investigating the consequences of the visual information available in the periphery (enlargement of the functional visual field) on the performance of navigation. Such an enlargement was assumed to help the operator estimate the distances between the vehicle and the objects in the environment and anticipate the vehicle's trajectory. A ''compromise'' between desktop and head-immersion navigations was needed in order to take the advantages of each while avoiding their respective drawbacks. For this purpose, a large image of good quality (as in desktop situations) was presented under a large functional visual field (as in head-immersive situations). The operator was not provided with a helmet, but an Ascension magnetic tracker allowed to take into account the operator's head movements (and in some cases to amplify them). The progressive integration of the interface properties was tested through performance evaluation of navigation along four successive sessions. It was hypothesized first that the performance of navigation would improve throughout the sessions (training effect). Second, thanks to the increase of simultaneously visible spatial information in some experimental conditions (enlargement of the functional visual field), the participants would be able to anticipate their path and to maneuver more safely than in the absence of such enlargment.

2 Materials

A graphic PC-based workstation was used to simulate 3-D wireframe environments composed of pyramids dispersed around a path, and of one cube representing the target at the end of this path. (See Figure 1a.) A 3-D vectorial graphic card (Matrox SM1281, 256 colors, 1280 × 1024 pixels) with the capacity for generating approximately 100,000 3-D, z-buffered, Gouraud-shaded facets per second was used to produce perspective views or scenes (See Figure 1b), simulating observer motion through the environment. Each scene was generated as if it had been seen by a 1.80 m tall observer. The scenes were displayed on a video projector that was 3 m high and 4 m wide. The observer's head was positioned at the center of projection of the scene 3.5 m from the screen, so that the observer's field of view (approximately 50 deg. vertical by 60 deg. horizontal) fit the geometrical field of view (Barfield & Kim, 1991; McGreevy & Ellis, 1986; Psotka et al., in press; and Sedgwick, 1991). The computer generated and displayed the scenes on the screen at a rate of 25 frames per second. Displacement through the simulated environment was controlled by the observer via manipulation of a joystick. The data from the joystick were fed into a simple inertial-dynamic model providing left / right rotation, forward (but not backward) translation with a

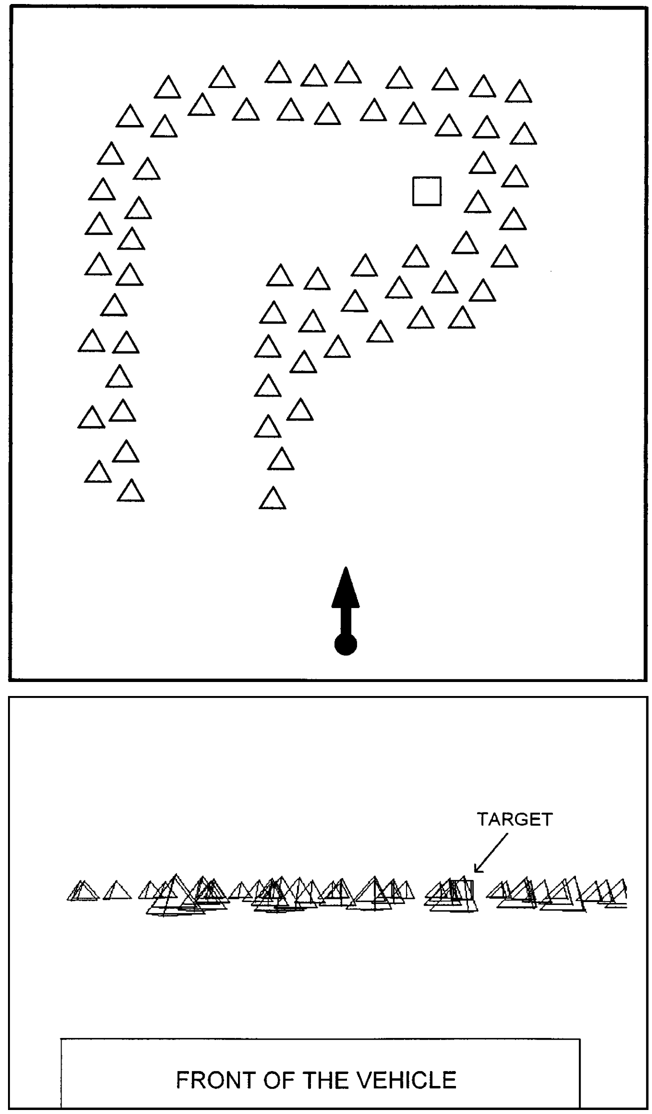

Figure 1. *Cartographic representation of an experimental environment (1a) with the corresponding scene from the observer's initial position (1b). In Figure 1a, the environment (about 120 m sides) comprises 64 white pyramids (2 m base) dispersed along the path and of one yellow cube (2 m side), representing the target at the end of the path. Since the separation between the pyramids is superior to 10 m, the vehicle (2 m side) can easily move along the path. The black arrow indicates the starting position and orientation of the vehicle. In Figure 1b, a (blue) rectangle at the bottom simulates the front of the vehicle (2 m wide).*

maximum speed of 4 m per second, immobilization (backward movement of the joystick), and all possible combinations of movements. A rectangle at the bottom of the screen indicated the front of the simulated vehicle

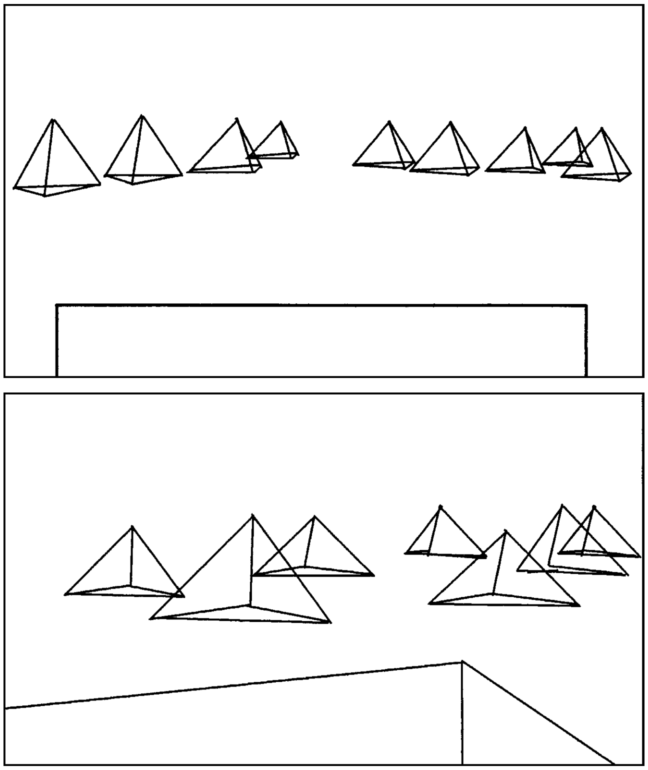

Figure 2. *Scenes taken along a path in Fixed Vision (a) and Mobile Vision (b) conditions. In Figure 2b, the rectangle corresponding to the front of the vehicle indicates that the observer's direction of gaze is to the right of the vehicle's direction of displacement.*

(See Figure 1b.) According to the condition of vision, the direction of gaze of the observer was coupled (or not) to the vehicle's direction of displacement.

The observer wore a captor recording the position of his / her head: ''A Flock of Birds'' developed by Ascension Technology Corporation, with six degrees of freedom (DOF) (three positions and three angles). In this experiment, only the rotations in the horizontal plane were recorded. The data were used to simulate the head movements according to three experimental conditions. In the Fixed Vision condition, there was no relationship between the head position and the direction of gaze, this latter remaining aligned with the front of the simulated vehicle. (See Figure 2a.) In the two Mobile Vision conditions, there was a 1:1 (Mobile Vision 1) or 1:2 (Mobile Vision 2) relationship between the head position and the direction of gaze. (See Figure 2b.) Thus, in Mobile Vision 1, a head rotation of 30 deg. to the left (the maximum) produced a 30 deg. apparent rotation to the left, and, in Mobile Vision 2, a 60 deg. apparent rotation to the left. In other words, the functional visual field was 60 deg. in Fixed Vision, 120 deg. in Mobile Vision 1 (60 deg. of initial aperture plus 30 deg. on each side), and 180 deg. in Mobile Vision 2 (60 deg. of initial aperture plus 60 deg. on each side). Since the scenes were projected on a flat screen fixed on a wall (and not in a helmet), the functional head movements were reasonably limited to 30 deg., in such a way that the scenes could be always entirely visible after head movements.

3 Procedure

Before starting the experiment, the participant practiced on the device for approximately thirty minutes. After this training period, none of the participants reported having difficulty in using the joystick, and all understood the dynamic display produced on the screen as simulating their own displacement within the environment. The features of the simulated environments used during the joystick practice sessions were different from those selected for the actual experiment. At the beginning of each trial the participant was located at the starting point, outside (in front of) the environment, and was required to locate the target (a yellow cube among the white pyramids), find the beginning of the path to the target, and follow this path as quickly and as accurately as possible until the target was reached (by colliding with it). The participant had to immediately return to the path if the vehicle went outside its limits.

4 Design

Twelve environments (six with their mirror images) were generated according to the complexity of the path from start to target. (See Figure 3.) The complexity was defined as the number of curves and changes in direction. Environment 1 and 2 had only one curve, while Environment 5 and 6 had three curves with two changes in direction. The length of the paths increased with their complexity. The participants were randomly assigned to

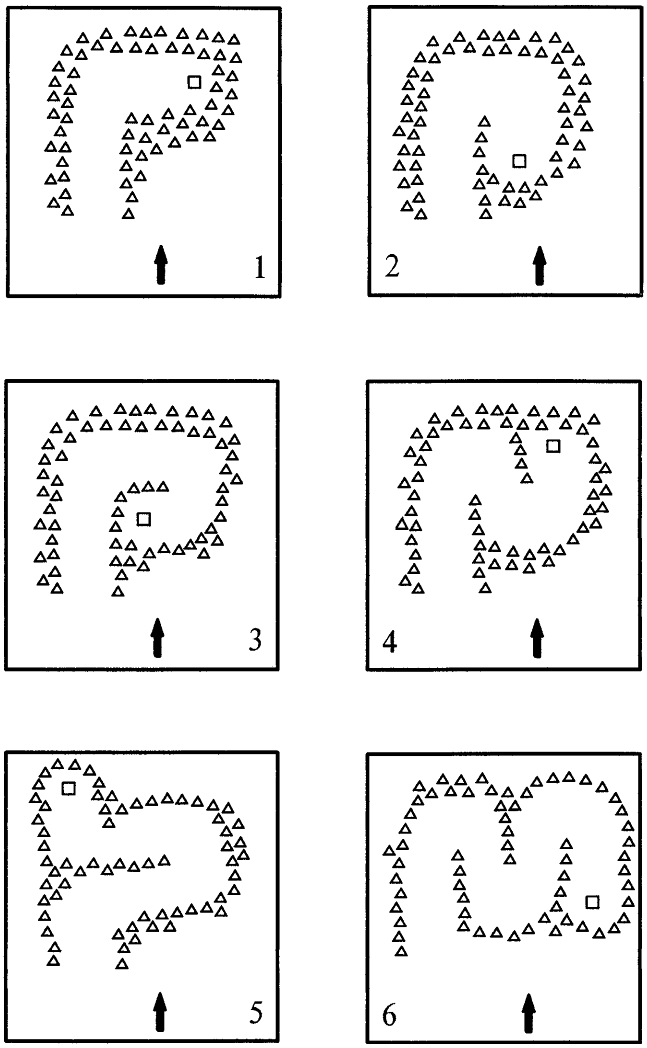

Figure 3. *Cartographic representation of the six environments used in the experiment (without their mirror image).*

three groups, one per vision condition. Each group performed four sessions (one session per day) involving the twelve environments. In each session, the environments were presented in random order. The participants were not provided with a map of the environment before or during the experiment. Each experimental session lasted about one hour, including the training period.

5 Participants

Nine women and nine men—either graduate students or laboratory staff members, aged 20 to 28 (mean: 23.3; SD: 2.7), with normal or corrected-to-normal vision—participated in all sessions of the experiment (three women and three men in each condition of vision). They were informed of the purpose of the study and verbally gave their consent.

6 Results

6.1 General Observations

The participants' comments given at the end of each experimental session are informative about their navigation strategies. Learning the environments was generally completed between Session 2 and 3. The mental image of the path was used to plan the displacement, and, during the movement, the participants concentrated mainly on the verification of the process and on the anticipation of the curves. Along the successive trials, they optimized their trajectory by finding a compromise between speed and accuracy: they progressively drove as smoothly as possible. However, on this point some differences appeared between the conditions of vision. (See examples in Figure 4.) In particular, in Fixed Vision the limits of the paths were not visible on a straight line and especially during a curve, where such information is decisive. In most cases, the Mobile Vision conditions were superior since they allowed the participant to ''go and see'' the curve without modifying the dynamics of the vehicle. Since the participants tried to anticipate their trajectory or stopped just before leaving the path, only a few exits were observed. Also, many stops occurred before or during a curve, which affected completion time (from start to target). Statistical analyses were carried out on completion time, stops (mean number and total duration), and the smoothness of the trajectories.

6.2 Completion Time

A three-way ANOVA (vision condition as a between-subject factor, environment and session as within-subject factors) showed that environment complexity (Environment 1 to 6) had an overall significant effect on completion time ($F^{(5,75)} = 817.9$, $p < 0.0001$), which was not surprising because the length of the path increased with the complexity of the environment. (See

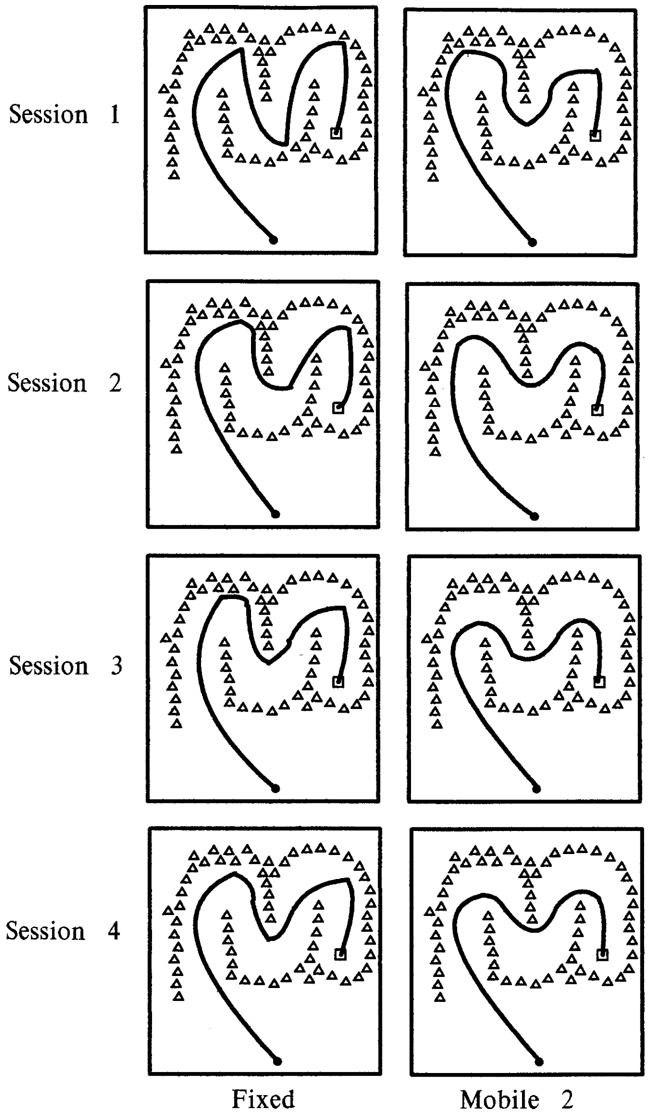

Figure 4. *Comparison, along sessions and between the two "extreme" conditions of vision, of two participants' trajectories performed on Environment 6. On the left (Fixed Vision) the rupture of the smoothness, corresponding to a stop before a curve, is still present in Session 4, while on the right (Mobile Vision 2), the trajectory is smooth after session 1.*

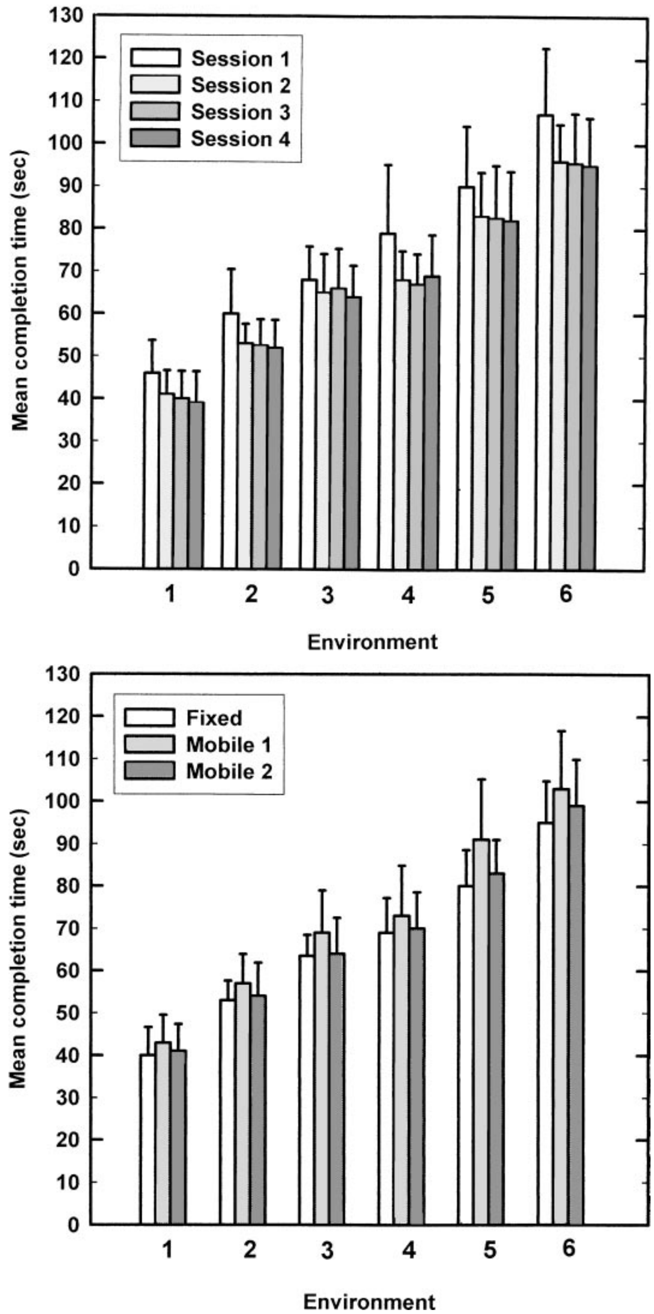

Figure 5. *Mean completion time (in seconds) by type of environment and session (a), and by environment and vision condition (b).*

Figure 5a.) The completion time significantly decreased between Session 1 and 4, $F^{(3,45)} = 14.22$, $p < 0.0001$, showing a training effect. Post-hoc tests (Tukey HSDs, $p < 0.05$) revealed that the completion time was longer in Session 1 than in the other three sessions, which did not differ significantly from each other. Lastly, although the completion time was longer in Mobile Vision 1 and globally shorter in the Fixed Vision condition, no significant main or interaction effect was found with the vision condition factor. (See Figure 5b.)

6.3 Stopping

A three-way ANOVA (vision condition as a between-subject factor, environment and session as within-subject factors) showed that the mean number of stops along the paths significantly increased between Environment 1 and 6 ($F^{(5,75)} = 63.84$, $p < 0.0001$), and decreased between Session 1 and 4 ($F^{(3,45)} = 7.03$, $p < 0.0005$). Tukey HSD tests ($p < 0.05$) showed that the mean number of stops decreased on Environment 5 for Session 3 and 4. The vision condition had no significant main or interaction effect. Another three-way ANOVA with the same design revealed that the total duration of the stops increased between Environment 1 and 6 ($F^{(5,75)} = 47.13$, $p < 0.0001$) and decreased between Session 1 and 4 ($F^{(3,45)} = 53.33$, $p < 0.0001$). The interaction between these two factors was significant: the duration was shorter after Session 1 for Environment 4, 5, and 6 (by Tukey's HSD tests.) (See Figure 6a.) The interaction between session and vision condition was also significant ($F^{(6,45)} = 3.40$, $p < 0.0075$). Tukey HSD tests revealed that the stops tended to be shorter under Mobile Vision 2, and were longer in Mobile Vision 1 than in Fixed Vision during Session 1 and 2, and were equivalent during Session 3 and 4. (See Figure 6b.)

6.4 Smoothness of Trajectories

In order to analyze the smoothness of trajectories, an index was computed on the basis of the frequency distribution of the instantaneous curve radius of each trajectory. The following formula was used:

$$r(m) = \frac{v(\mathrm{m/sec})}{w(\mathrm{radians/sec})},$$

where r corresponds to the curve radius, v is the instantaneous speed, and w is the absolute instantaneous rotation speed. The curve radius is converted in decimal logarithm. If the vehicle nearly stops and makes a single rotation, the curve radius is very small (<1), and the logarithmic value of r is negative. If the vehicle makes a combination of translation and rotation, since the maximum linear speed is 4 m / sec and the maximum rotational speed is 0.14 radians / sec, the curve radius is >1 and its logarithm is >0. If before each curve the participant stops and makes a single rotation, the distribution of curve radii will be bimodal, with one spike centered

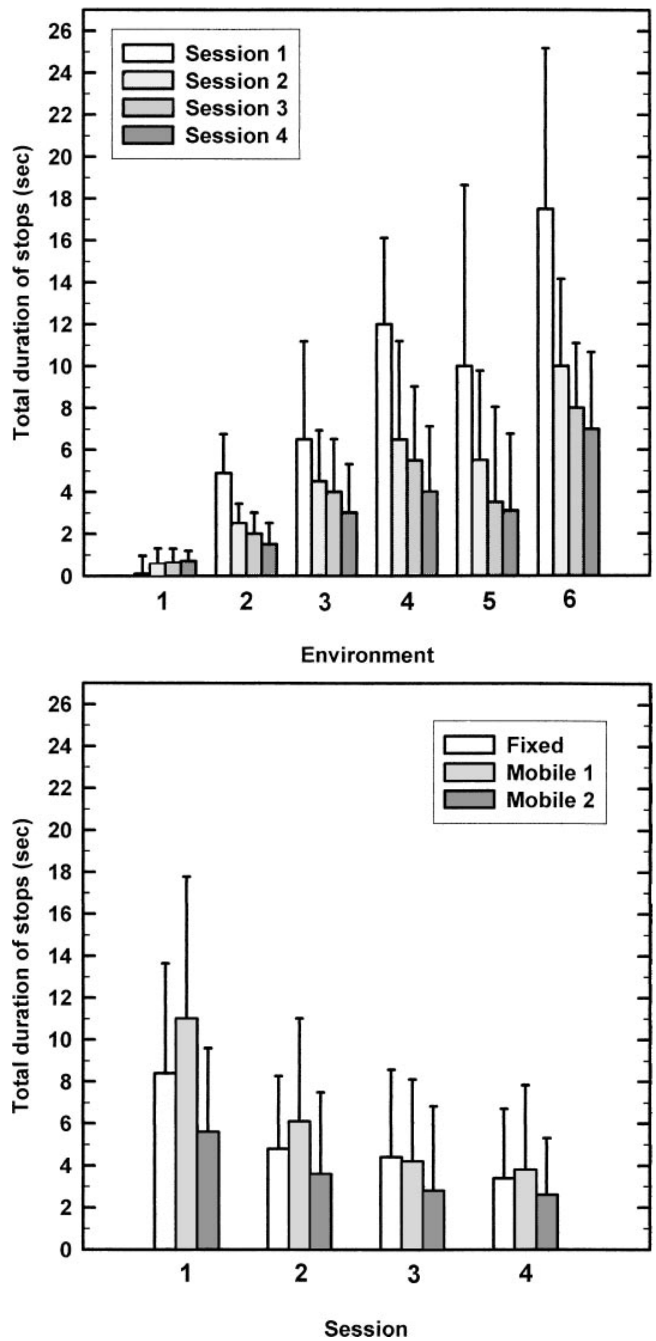

Figure 6. *Total duration of stops along a path (in seconds) by environment and session (a), and by session and vision condition (b).*

on negative values of the logarithm and the other spike centered on positive values. If the participant makes a smooth (or curvilinear) trajectory, the distribution will rather be unimodal and centered on a value >0 of the logarithm of the curve radius. For each trajectory, the distribution of the logarithm of the curve radii was computed and distributed in categories from -5 to $+5$. (The values at the starting point were suppressed.) The distributions were normalized, the occurrences of curve radii in each category being expressed as a percentage of the total number of occurrences for each trajectory.

These occurrence percentages were submitted to a four-way ANOVA, with vision condition (Fixed Vision versus Mobile Vision 2) as between-subject factor, and session, environment, and category ($n = 10$) as within-subject factors. Results first showed a significant effect of category ($F^{(9,90)} = 799.77$, $p < 0.00001$), revealing that the distribution of curve radii was nonmonotonic. There were two ''dominant'' spikes, one centered around Category 4 (single rotation, $2 < \log(r) < -1$, 3% to 8% of occurrences), and one centered around Category 7 (curvilinear path, $1 < \log(r) < 2$, 50% to 55% of occurrences). Second, the interaction between category and session was significant ($F^{(27,270)} = 6.33$, $p < 0.00001$). Along the successive sessions, Category 4 came from 8% to 4% of occurrences, while Category 7 came from 51% to 56% of occurrences. Thus, smoothing probably results from learning. Third, there was a significant interaction between category and environment ($F^{(45,450)} = 35.12$, $p < 0.00001$): Category 4 increased from Environment 1 to 6, while Category 7 decreased from Environment 1 to 6. In other words, the trajectories were more smoothed in Environment 1 (easier) and less smoothed in Environment 6 (more difficult). These results are coherent with those of the previous analyses. Finally, there was a significant interaction between vision condition, session, and category ($F^{(27,270)} = 1.74$, $p < 0.014$). There was a tendency (although nonsignificant) of Mobile Vision 2 to produce more-smoothed trajectories (spike of Category 4 less important, spike of Category 7 more important) along the successive sessions. However, partial analyses revealed that Mobile Vision 2 improved the smoothness of trajectories only in Session 1 ($F^{(9,90)} = 3.79$, $p < 0.0004$). Thus, the differences between vision conditions were reduced by training.

7 Discussion

This study investigated the consequences of the visual information available in the periphery on navigation performance. A fixed-vision condition and two mobile-vision conditions (giving a variable width of functional visual field) were compared in six environments of different complexity in four successive sessions. A global improvement in performance (completion time, and number and duration of stops along a path) was observed throughout the sessions, showing the gradual integration of the properties of the simulation device. An increase in environment complexity generally decreased performance. Significant differences between the vision conditions were obtained for the stop duration along the paths: higher performance was observed when a 180 deg. visual field was available (Mobile Vision 2) and allowed for better anticipation of the curve. Increasing rotational movement in peripheral vision improves performance and confirms the importance of peripheral visual mechanisms (Johansson & Börjesson, 1989; Warren et al., 1991). It should be noted that Mobile Vision 1 did not lead to better performance than Fixed Vision, probably because the gain in functional visual field was not sufficient. The presence and duration of stops along a path revealed the operators' difficulty at controlling the translation and rotation of their vehicle at the same time. When the curve angle was large (approximately 180 deg.), the restricted visual field did not allow the operator to see the ongoing environment and thus to anticipate the trajectory. This might also explain why the operators stopped the vehicle in order to perform a single rotation.

One possible interpretation of this result would be that, at least at the beginning, the Mobile Vision conditions increased the mental load of navigation, and that the informational gain in Mobile Vision 1 was not sufficient to compensate for this supplementary load. This would explain why during the first two sessions the stop durations were higher in Mobile Vision 1 than in Fixed

Vision, and were not shorter in the two last sessions. In contrast, the informational gain given by Mobile Vision 2 was sufficient to improve performance, probably because having a 180 deg. functional visual field was crucial in this situation. In other words, a gain was provided only when the visual field was sufficiently large and only after learning. Furthermore, the analysis of stop durations provides estimates of the smoothness of the paths (combination of the linear and rotational speeds). A greater number of smooth paths could be observed in the last two sessions and in Mobile Vision 2. Because hand and head movements were taken into account, thus allowing a ''perception-action'' cycle (Flach, 1990; Gibson, 1979; Heft, 1994), this experimental situation can be considered as a step towards telepresence. According to several authors, two factors (among others) that limit telepresence are difficulties in integrating the properties of a new device (see, for example, Held & Durlach, 1991) and the mental load (see, for example, Henry, 1992; Stone, 1992; and Arthur, 1996). Such factors can also be assumed to have limited telepresence, and thus performance, in the present study.

In summary, designing realistic and functionally efficient human-machine interfaces for spatially oriented control tasks remains a difficult problem, and much still needs to be done. Because they are a functional part of human-environment interactions, human-machine interfaces should represent the functional structure of the work situation in a way that matches the immediate task and the perceptuomotor capabilities of the operator. Thus, in order to define useful guidelines for the conception of valuable human-machine interfaces, especially in the area of driving remote-controlled vehicles, we need a better understanding of the perceptual, cognitive, and motor processes involved in ''natural'' navigation tasks. One must consider that the operator's behavior is usually decisive, especially when a ''temporal emergency'' dominates the situation (as in hostile environments). In situations where rapidity is the key factor, the human-device interface must be able to act quickly in response to the operator's actions (even reflex actions): the real efficiency of the interface will thus be demonstrated in emergency situations, more than in usual ones. In such conditions, although remote-controlled tasks are not ''natural,'' it is highly likely that operators performing them use their own experience and skills about displacement through environment (as in locomotion or vehicle driving). Thus, one of the objectives of designers and engineers is to render these situations as natural as possible by affording ''telepresence'' (Held & Durlach, 1991; Stone, 1992). A major issue is the format of visual information, and some important components of the navigation task are the location of the vehicle, the control of its displacement, and the interaction between the two. As a conclusion, although it was restricted from 60 deg. to 180 deg. of functional visual field, such a compromise between desktop and immersive systems allowed the collection of rotational information and facilitated the vehicle's maneuvering. A guideline for further research would be to use immersive situations (or fixed multiple-camera systems projecting on a 180 deg. flat or curved screen) combined with more-informative virtual environments (for instance, as suggested by several participants, with groundplane information and with a triangle representing the front of the vehicle).

Acknowledgements

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References

Alfano, P. L., & Michel, G. F. (1990). Restricting the field of view: Perceptual and performance effects. *Perceptual and Motor Skills, 70,* 35–45.

Arthur, E. J. (1996). *Orientation specificity in the mental representation of three dimensional environments.* Unpublished thesis, University of Minnesota.

Arthur, E. J., Hancock, P. A., & Chrysler, S. T. (1997). The perception of spatial layout in real and virtual worlds. *Ergonomics, 40,* 69–77.

Barfield, W., & Kim, Y. (1991). Effect of geometric parameters of perspective on judgements of spatial information. *Perceptual and Motor Skills, 73,* 619–623.

Bengston, J. K., Stergios, J. C., Ward, J. L., & Jester, R. E. (1980). Optic array determinants of apparent distance and size in pictures. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 751–759.

Flach, J. (1990). Control with an eye for perception: Precursors to an active psychophysics. *Ecological Psychology, 2,* 83–111.

Foreman, N., & Wilson, P. (1996). Can reality be simulated?: Uses in psychology of 3-Dimensional computer-generated environments (virtual reality). *Psikologichiskii Zhournal, 17,* 64–79.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Grunwald, A. J., Ellis, S. R., & Smith, S. (1988). Mathematical model for spatial orientation from pictorial perspective displays. *IEEE Transactions on Systems, Man, and Cybernetics, 18,* 425–437.

Heft, H. (1994). The relevance of Gibson's ecological approach to perception for environment-behavior studies. In G. T. Moore & R. W. Warans (Eds.), *Advances in environment, behavior, and design* (Vol. 4). New York: Plenum.

Held, R., & Durlach, N. (1991). Telepresence, time delay and adaptation. In S. R. Ellis (Ed.), *Pictorial communication in virtual and real environments,* 232–246. London: Taylor & Francis.

Henry, D. (1992). *Spatial perception in virtual environments: Evaluating an architectural application.* Unpublished master's thesis, University of Washington.

Hightower, J. D., Spain, E. H., & Bowles, R. W. (1987). Telepresence: A hybrid approach to high-performance robots. *Proceedings of the Third International Conference on Advanced Robotics* (ICAR 87).

Johansson, G., & Börjesson, E. (1989). Toward a new theory of vision studies in wide-angle space perception. *Ecological Psychology, 1,* 301–331.

McGreevy, M. W., & Ellis, S. R. (1986). The effect of perspective geometry on judged direction in spatial information instruments. *Human Factors, 25,* 439–456.

Mestre, D., Cavallo, V., & Péruch, P. (1986). Definition of an on-board visual aid for piloting large ships. In A. G. Gale, M. H. Freeman, C. M. Haslegrave, P. A. Smith, & S. P. Taylor (Eds.), *Vision in Vehicles,* 257–264. Amsterdam: North-Holland and Elsevier Sciences Publishers BV.

Miller, D. P., & McGovern, D. E. (1988). A laboratory-simulation approach to the evaluation of vision systems for teleoperated vehicles. *Proceedings of the International Symposium on Teleoperation and Control.*

Neale, D. C. (1996). Spatial perception in desktop virtual environments. *Proceedings of the 40th annual meeting of the Human Factors and Ergonomics Society,* 1117–1121. Santa Monica, CA: Human Factors and Ergonomics Society.

Padmos, P., & van Erp, J. (1996). Driving with camera view. In A. G. Gale, I. D. Brown, C. M. Haslegrave, & S. P. Taylor (Eds.), *Vision in Vehicles V,* 219–228. Amsterdam: North-Holland.

Péruch, P., Mestre, D., Pailhous, J., & Savoyant, A. (1993). Visual interfaces in driving remote-controlled vehicles. In A. G. Gale, I. D. Brown, C. M. Haslegrave, H. W. Kruysse, & S. P. Taylor (Eds.), *Vision in Vehicles IV,* 232–247. Amsterdam: North-Holland.

Péruch, P., Vercher, J. L., & Gauthier, G. M. (1995). Acquisition of spatial knowledge through visual exploration of simulated environments. *Ecological Psychology, 7,* 1–20.

Péruch, P., May, M., & Wartenberg, F. (1997). Homing in virtual environments: Effects of field of view and path layout. *Perception, 26,* 301–311.

Psotka, J., Lewis, S. A., & King, D. (in press). Effects of field of view on judgments of self-location: Distortions in distance estimations even when image geometry exactly fits the field of view. *Presence: Teleoperators and Virtual Environments.*

Rieser, J. J., Hill, E. W., Talor, C. R., Rosen, S., & Bradfield, A. (1992). Visual experience, visual field size, and the development of nonvisual sensitivity to the spatial structure of outdoor neighborhoods explored by walking. *Journal of Experimental Psychology: General, 121,* 210–221.

Ruddle, R. A., Randal, S. J., Payne, S. J., & Jones, D. M. (1996). Navigation and spatial knowledge acquisition in large-scale virtual buildings: An experimental comparison of immersive and desk-top displays. *Proceedings of the 2nd International FIVE Conference,* 125–136.

Sedgwick, H. A. (1991). The effects of viewpoint on the virtual space of pictures. In S. R. Ellis (Ed.), *Pictorial Communication in Virtual and Real Environments,* 460–479. London: Taylor and Francis.

Slater, M., & Usoh, M. (1993). Simulating peripheral vision in immersive virtual environments. *Computers and Graphics, 17,* 643–653.

Stone, R. (1992). Virtual reality and telepresence. *Robotica, 10,* 461–467.

Warren, W. H., Mestre, D., Blackwell, A. W., & Morris, M. W. (1991). Perception of circular heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 28–43.

Wilson, P. N. (1997). Use of virtual reality computing in spatial learning research. In N. Foreman & R. Gillett (Eds.), *Handbook of spatial research paradigms and methodologies.* Vol. I: Spatial cognition in the child and adult, 181–206. Hove, UK: Psychology Press.