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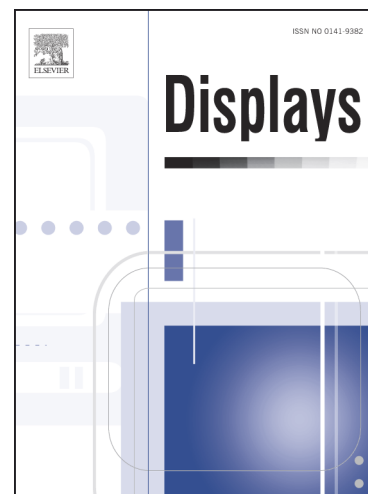
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Misperception of egocentric distances in virtual environments: more a question of training than a technological issue?

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Abstract

Findings from virtual reality applications in general and driving or flight simulators in particular, are frequently generalized to the study of human behavior. Thus, it is crucial to ensure that the virtuality of the experimental setup has little or no effect on perception of space and motion. Most studies show that observers immersed in virtual environments (VE) perceive virtual space as compressed relative to the real world, resulting in systematic underestimations of egocentric distance. Parallax and stereopsis, known to be important depth cues for distance perception, at least for short distances, are rarely used together in driving simulators, so their interactive role during driving tasks is still not clear. Inter-individual differences in misperception are also referred to, though few studies have explored this. The aim of this study was, first, to determine whether egocentric distance perception in driving simulation depends on two depth cues, binocular disparity and motion parallax, and, second, to examine the effect of inter-individual differences. Several conditions were tested, both with and without stereoscopic vision of the scene and/or motion parallax of the head. We focused first on a range of long distances, 40 to 80 m (Experiment 1) and subsequently widened the range to distances from 5 to 80 m, thereby including short distances where stereopsis should be more relevant (Experiment 2). The study reveals great inter-individual variability, clearly distinguishing two participant profiles. However, results suggest that such differences do not depend on the availability of motion parallax and stereoscopic vision.

The findings also show that an initial familiarization phase, under conditions similar to those of the experiments, can be predictive of participants' perceptual behavior.

Keywords: Distance perception; parallax; stereoscopy; inter-individual variability.

1. Introduction

Since the emergence of modern virtual reality (VR) tools, car manufacturers have increasingly turned to driving simulation as a way to test future products without needing to build physical mockups. In addition, manufacturers address road safety issues through advanced driving assistance systems (ADAS) intended to combine efficiency with minimum cost and maximum safety, as compared to real open-road tests. This recourse to VR raises the question of ensuring that the driver's performance and behavior in the simulator are the same as in real life, in order to validate transfer from virtual to real cars.

To be useful for car manufacturers, driving simulators need to induce human perception and behaviors as close as possible to reality. The crucial question of the realism of simulators has become a major issue both for the industry and for scientists interested in human perception. One of many challenges lies in ensuring that the virtuality of the experimental situation has little or no effect on space and motion perception [1].

A major problem encountered in driving simulators, or in VR devices more generally, concerns distance perception in virtual environments (VE), especially when scale 1 (scale 1 means that the ratio between the size of representation and the size of what it represented is equal to 1) is needed. It has been well established that distances are misperceived in VEs, and part of this misperception is believed to consist in a compression of egocentric distances [2-7]. Distances are typically underestimated in locomotor pointing tasks [8], and this misperception has also been observed in driving simulation [9], regardless of velocity [10] or visual context (monocular vs. binocular, [11]). The origin of these perceptual errors observed in VEs is not yet fully clear, even though such errors are commonly observed with many different types of VR systems. As explained below, numerous potential causes have been examined, for instance motion parallax [12] or binocular disparity [13]. Distance information comes from a variety of sources and is mediated by nearly all the senses, including visual, auditory or proprioceptive systems. Contextual and personal, idiosyncratic variables may also influence distance perception [14].

A variety of sources of information about spatial relations between objects in the environment are used by the human visual system. Traditionally, a distinction is made between two categories of depth cues: pictorial depth cues and non-pictorial depth cues [15]. Sources of depth information from 2-D images such as pictures are called pictorial cues [16], and include occlusion, relative size, relative density, height in the visual field, and aerial perspective [15]. Visual cues from a 3D environment are called non-pictorial cues. Several are thought to influence scale perception in virtual environments, for instance quality of graphics [17], field of view [18], or time delay in head-motion parallax [19]. The oculomotor system may also yield non-pictorial depth cues, for example through convergence, accommodation and parallax. Accommodation means that the curvature of the lens is adjusted by the brain according to the distance from which objects are viewed. Convergence allows both eyes to be moved separately, so that the gaze line of each eye converges at the object's location. The resulting binocular disparity between the two images generates stereoscopic cues to relative distance [20]. It is well known that binocular disparity decreases with distance from the observer to the observed object, even though humans are highly sensitive to binocular disparity and can detect depth differences corresponding to horizontal images with disparities as small as a few seconds of arc [21]. According to Schiff [22] and Loomis and Knapp [23], binocular disparity could be used for perceiving very long distances. However, to our knowledge, there has been little investigation of stereopsis at long distances, most of the studies focusing on interaction/action space (which extends from the far boundary of personal space to about 30 m or so, which is considered the maximum range over which a non-mechanized viewer can interact over a short period of time) [15, 24]. At these short distances, lack of binocular disparity may impair distance perception [25, 26]. At longer distances, however, binocular disparity is less effective as a depth cue [13, 27]. Non-pictorial depth cues are also derived from motion. When we move our head while watching two objects placed at different distances from us, the relative motion of each of the two objects on the retina, generated by observers' self-motion, is called motion parallax, and induces subjective depth cues [28]. Motion parallax is a monocular cue, since closing one eye does not affect depth perception [29].

Parallax seems to have little impact on the estimation of distances, at least for short distances [12], but it provides information about objects' relative position in depth [30, 31]. However, studies conducted in real environments showed that head-motion parallax can be helpful for the perception of distance, although only in cases where more relevant cues are not available [32, 33].

All this points to the need to study the separate and joint influence of stereopsis and motion parallax on distance perception over a wide range of distances in VR, and particularly driving simulation. In the work reported here, we chose to focus only on visual, non-pictorial, interactive information, since these are the factors most frequently suggested as crucial [14].

For driving simulation to mimic real situations as closely as possible, the displacement and speed must be quite high, since the driver generally experiences huge variations of position and speed over a wide range of distances. Consequently, non-pictorial information, mainly parallax and binocular disparity, are likely to play a preponderant role. However, most driving simulators (whether static or dynamic) do not use stereoscopic displays nor head motion tracking, and the observed lack of realism may be due to the absence of disparity and/or motion parallax cues. We therefore tested the influence of stereoscopic display and motion parallax on the perception of distances in driving simulation. In addition, because driving forms part of daily routine, perception of distance is also likely to be impacted by individual characteristics. Recent studies reveal inter-individual differences in perceived egocentric distance [25, 26, 34-39], even though few examine this explicitly. Furthermore, we characterize inter-individual variability, on the basis of individual performance, in order to reveal possible different strategies. Our study focuses on distance perception in the presence of different non-pictorial cues, testing long distances in experiment 1 and a wider range of distances (including short ones) in experiment 2. Our hypothesis was that if inter-individual differences in distance estimation are evidence of different perceptual processes, perceptive profile could be drawn on the basis of different uses of stereoscopic vision and/or head motion parallax.

2. Experiment 1

2.1 Methods

2.1.1 Participants

Fourteen participants (5 women and 9 men, mean age 27 ± 3 years) participated in this experiment. All had held a driving license for over 5 years. All had normal or corrected to normal vision. Participants were tested for binocular vision acuity (RandotTest[®]), and completed a questionnaire determining their sensitivity to motion sickness (Reason and Brand Motion Sickness Susceptibility Questionnaire (MSSQ)[40, 41]. In a case a participant replied that he/she felt sick or nauseated frequently in cars over the last ten years, he/she was then excluded from the study (one person was excluded). The level of experience with VR systems was rated by the participants on a scale ranging from 0: none to 3: expert. They all signed an informed consent form informing them about the conditions of the experiment, their right of withdrawal and the obligation not to drive for two hours after the end of the session, in accordance with the Helsinki convention. The protocol was approved by the institutional review board of the Institute of Movement Sciences. The data were analyzed anonymously.

2.1.2 Experimental device

A static driving simulator was positioned within an immersive VR display, namely a Cave Automatic Virtual Environment (CAVE) housed at the Mediterranean Virtual Reality Center. The CAVE is a 3-m deep, 3-m wide, and 4-m high space with three vertical screens for walls and a horizontal screen for the floor. The three vertical surfaces were back-projected, and the ground received direct projection with a 1,400-1,050-pixel resolution and a 60-Hz frame rate. Each projection surface was illuminated by two video projectors, which were used to generate passive stereoscopic images. Each pair of projectors was equipped with colorimetric filters, and the same color filters were mounted on the three-dimensional passive 3D glasses (INFITEC[®] colorimetric system) worn by the subjects. A stereo separation system

(Infitec®) was used to separate the images received by the two eyes. On these glasses were placed targets for the head position tracking system (ART-TRACK®). This system was used to record the participant's head position and orientation at 60 Hz and for real-time updating of the stereoscopic images relative to the participant's point of view. The participant was seated in a bucket seat.

The virtual environment was simulated with in-house software (ICE®) and was divided into two distinct parts, the cabin and the external scene. The cabin, representing the interior of the car (the dashboard and the rear-view mirror were not part of the physical simulator, see Fig. 1), was always simulated with 3D parallax and stereoscopy. There was an additional speed gauge on the dashboard, simply represented by a grey rectangle positioned above the dashboard, with a small orange zone in the upper part corresponding to a target speed of between 59.5 kph and 60.5 kph (see figure 1). A green cursor moved up and down on this gauge according to the current speed of the participant's virtual car. On the other side, the external environment was rendered in graphic 3D, but stereoscopy and parallax could be turned ON or OFF independently, according to the experimental condition.

The virtual environment consisted in a two-lane straight road 1 km long and its surroundings. This environment contained two successive scenes. The first (Fig 1, center) was an urban scene composed of many buildings and adjacent roads (but no traffic), reproduced at scale 1. It was designed mainly to provide rich optical flow and rich visual information, so that the participants could build a metric of the environment and correctly perceive their speed. The second (Fig 1, right) was a rural scene with no buildings but surrounded by roadside grass and two textured walls (160 cm high), creating a "corridor". Two speakers located behind the front screen projected the sound of the vehicle.

2.1.3 Task

For all participants, the experiment took place in daytime. The only available commands were the steering wheel, accelerator and brake pedals. The seated participant drove a car, *Ca*, initially stationary in the right lane, and had to accelerate from 0 to 60 kph before leaving the urban part of the scene.

He/she had to maintain this constant speed until the end of the trial and to drive toward a vehicle *Cb* (using the additional speed gauge on the dashboard), parked in the right lane 480 m from the initial position of *Ca* (thus not visible from the starting point). Then, he/she had to shift to the left lane as soon as *Ca* reached the rural scene, in order to overtake *Cb*.



Figure 1: Left: Photograph of participant seated on static driving simulator in operation. Center : screenshot of the first part of the simulated environment (urban scene). Right : Screenshot of the second part of the simulated environment (rural scene).

When the driver was at a certain distance (varying between 40 m, 50 m, 60 m, 70 m and 80 m) from vehicle *Cb*, this latter suddenly disappeared. The participant was then requested to continue driving straight ahead, maintaining speed, and to press a button located on the steering wheel when he/she believed that his/her car was exactly beside *Cb*'s position, i.e. the front of his/her car exactly aligned with that of the front of the target car (as viewed before its disappearance). To minimize the spatial cues that could be used to locate *Cb*, special shaders were applied to the textures of the road, the roadside grass and both sides of the walls. These shaders were systematically applied from a distance of 28 m in front of the participant's current position in the environment. This ensured that, whatever the distance at which *Cb* disappeared, all adjacent textures were uniform and thus non informative.

Before the experimental session, each participant took part in a training session designed to ensure that he/she understood the requirements of the task and adopted reproducible driving behavior. This phase

also enabled us to characterize participants' behavior while learning the task, and at the same time familiarized them with the device.

The training session included two blocks of 20 trials each without parallax or stereoscopy on the external environment. In the first training block, C_b remained visible throughout the entire trial (visual closed-loop phase), allowing the participant to get used to the task and to improve accuracy. In the second block (visual open-loop phase), C_b disappeared at a random distance (between 40 m and 80 m with a 1 m step). The distances used during this phase differed from those used during the experimental session, to ensure that the participant would learn the task rather than the stimulus.

Once the training session was over, the experimental session per se began. Participants encountered four different visualization conditions: 1/ a control condition (CC), without parallax or stereoscopy; 2/ a parallax condition (PC), which introduced parallax on the surroundings but no stereoscopy; 3/ a stereoscopic condition (SC), which introduced stereoscopy on the surroundings but no parallax; and 4/ a total condition (TC) with both parallax and stereoscopy.

Participants performed 5 trials in each of the four conditions combined with the 5 disappearance distances, resulting in a total of 100 trials, presented in 4 different blocks (one per condition) separated by a 5 min rest period. The order of presentation of the conditions and distances was completely randomized and differed for each participant. The total duration of the experiment was 90 min.

2.1.4 Data analysis

Data were recorded at a sampling frequency equal to the rate of the simulation loop (100 Hz). These data are speed of vehicle C_a , position of vehicles C_a and C_b , distance between C_a and C_b on the longitudinal axis, and time of disappearance of C_b . Position of C_a relative to C_b when the participant pressed the response button on the steering wheel is also reported for each trial. This measure, called Relative Error (RE), has a negative value when the response preceded overtaking (interpreted as an underestimation of the distance) and a positive value when C_a had already overtaken C_b (interpreted as an overestimation).

During the learning session, the disappearance distance is randomly determined in a range from 40 m to 80 m, so the recorded performance had to be normalized to enable comparison between all trials. We thus computed the perceived distance as follows:

$$(\text{Distance of disappearance of Cb}) + (\text{Relative error}).$$

This perceived distance allowed us to compute an index of performance as follows, in order to compare errors produced at different distances:

$$(\text{Perceived distance}) * 100 / (\text{Distance of disappearance of Cb})$$

This allowed us to compare perceived distance percentages for different disappearance distances. Thus, an index of 100% indicated a perceived distance exactly equal to the distance to be estimated, whereas this index tended toward 0% when the distance was underestimated. An overestimation gave a score higher than 100%.

2.1.5 Statistical analysis

2 X 2 X 5 [STEREOSCOPY X PARALLAX X DISTANCE] repeated measures ANOVAs were used to assess the influence of distance and stereoscopic vision and motion parallax on distance perception. Hierarchical ascending classification (HAC) by Ward's criterion based on RE was used to classify participants in distinct groups and to bring to light inter-individual differences.

Then, a N X 2 X 2 X 5 [GROUP X STEREOSCOPY CONDITION X PARALLAX CONDITION X DISTANCES] (where N is the number of groups) repeated measures ANOVA was calculated to confirm the grouping and to assess the influence of distance and the two depth cues on distance perception for each group. T-tests were used to assess the significance of expertise effects.

2.2 Results

Interestingly none of the participants noticed any difference according to whether the parallax and stereoscopy were present or not. Actually, no one was able to specify what exactly the differences between conditions were. Half the participants reported that the distance of disappearance of vehicle *Cb* varied between blocks, and four said that the speed at which they had to move varied from one block to another (which was obviously false). Three participants reported a forward movement for *Cb* (which was obviously false), despite having been told that it was static throughout the experiment.

2.2.1 Analysis of relative error as a function of condition and distance

The average relative error (as measured by the distance between *Cb* and *Ca* when participants pressed the button) was -15.04 m (overall underestimation), with a standard deviation of 16.64 m. A Lilliefors normality test performed on the mean relative error of each participant in each condition showed that data followed a normal distribution. A 2 stereoscopy condition* 2 parallax condition* 5 distances repeated measures ANOVA was then performed. This analysis revealed no significant effect of condition on performance ($F(1, 13) = 0.43$, $p = 0.525$ for stereoscopic condition and $F(1, 13) = 1.03$, $p = 0.327$ for parallax condition), and no interaction between distance and visual condition ($F(12, 1380) = 0.15$, $p = 0.999$). However, the ANOVA yielded a significant effect of disappearance distance on performance ($F(4, 13) = 20.76$, $p < 0.001$). Mean relative error and standard deviation increased with distance (figure 2). Post hoc Tukey's tests revealed that the mean relative error in the 80m condition was significantly greater than in all other distance conditions ($p < 0.001$, $p < 0.001$, $p < 0.001$, $p = 0.015$ respectively for 40m 50m 60m and 70m). The mean errors as a function of distance and condition are presented in figure 2.

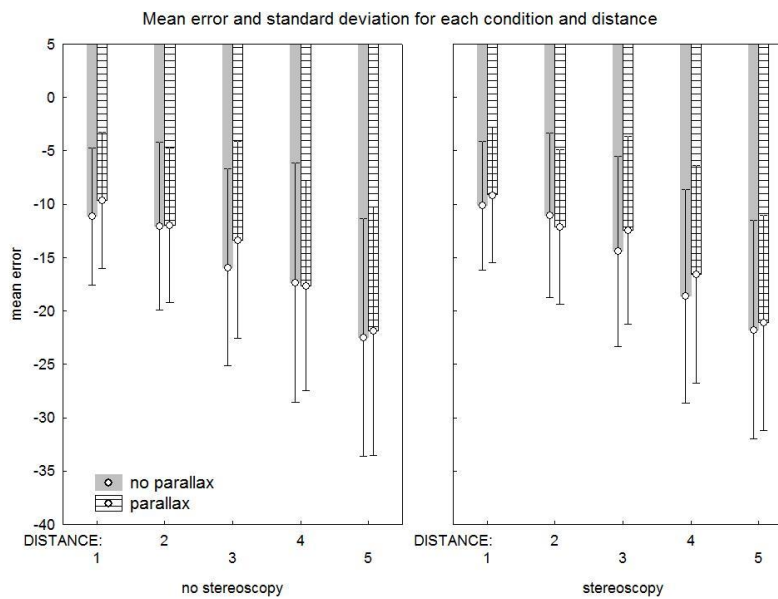


Figure 2: mean errors as a function of distance and condition.

2.2.2 Inter-individual differences

It can be seen from figure 2 that standard deviation has high values. From a visual inspection of individual data, we found that not all participants showed the reported underestimation; in fact, participants appeared to have very different error profiles. Analyses were performed to assess whether the participants could be divided into performance-based categories. A hierarchical ascending classification (HAC) by Ward's criterion (figure 3) showed that it was possible to divide the sample into two distinct categories based on relative error: Group 1 composed of 7 participants (6 men and 1 woman) and Group 2 composed of 7 participants (3 men and 4 women). This analysis showed that group 1 achieved an average error of $-2.62 \text{ m} \pm 10.39$ whereas group 2 exhibited larger errors (on average, $-27.45 \text{ m} \pm 11.95$). Individual data are presented in table 1.

	Group 1							Group 2						
	mean							mean						
							-2.62							-27.45
							10.39							11.95
Mean	+6.24	-8.07	-3.16	-7.21	+2.13	-3.16	-5.12	-20.18	-30.45	-21.87	-21.39	-21.33	-42.20	-34.76
SD	7.81	6.03	6.00	4.23	4.98	4.90	5.68	4.76	7.40	10.23	3.99	4.87	12.21	7.31

Table 1: Relative Error and Standard Deviation for both groups and each participants.

Next, a 2 groups x 2 stereoscopy condition x 2 parallax condition x 5 distances repeated measures ANOVA was performed on relative error. It yielded a significant effect of group ($F(1, 12)=43.42$, $p<0.001$), a significant difference in the impact of disappearance distance ($F(4, 48)=34.99$, $p<0.001$) (figure 4), and no significant effect of condition ($F(1, 12)=0.39$, $p=0.54$ for stereoscopy and $F(1, 12)=0.96$, $p=0.35$ for parallax).

Interaction effects were also analyzed, yielding no significant interaction between condition and distance ($F(12, 1360)=0.39$, $p=0.97$), no significant interaction between condition and group ($F(1, 12)=0.32$, $p=0.58$), but a significant interaction between distance and group ($F(4, 48)=9.90$, $p<0.001$). A post hoc Tukey's test revealed no significant difference in mean relative error for 40m, 50m, 60m, and 70m for Group 1. It also revealed that the mean relative error was always significantly greater for each increase in distance for Group 2 ($P<0.001$ for all cases), showing that the difference between the two groups increased with the distance to be estimated. In other words, Group 2 clearly appeared more likely than Group 1 to underestimate distance in the driving simulator.

A 2 groups * 2 stereoscopy condition * 2 parallax condition * 5 distances repeated measures ANOVA was performed on standard deviation. This analysis revealed no significant effect of condition on variability ($F(1, 12)=0.12$, $p=0.91$ for stereoscopic conditions and $F(1, 12)=1.39$, $p=0.26$ for

parallax conditions), no significant effect of groups ($F(1, 12) = 4.18, p = 0.06$), but a significant effect of distance ($F(4, 48) = 14.88, p < 0.001$) showing that variability increases when the distance to be estimated increases.

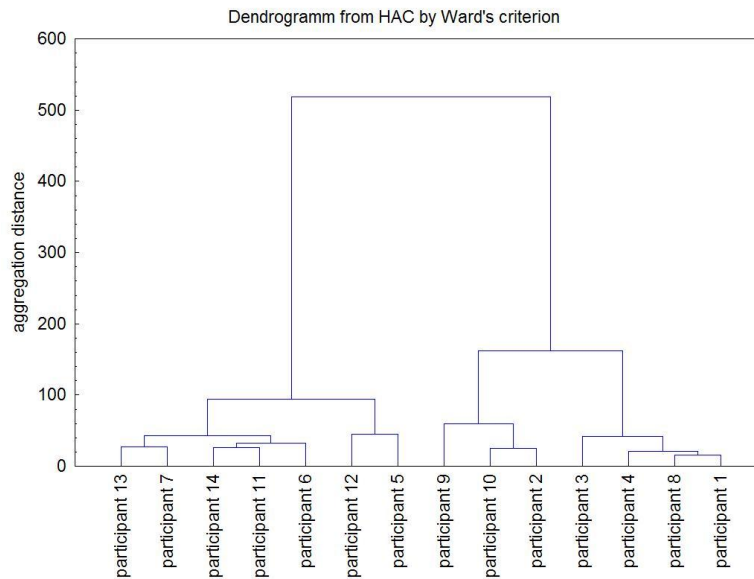


Figure 3: Hierarchical ascending classification by Ward's criterion based on RE (Euclidean distance).

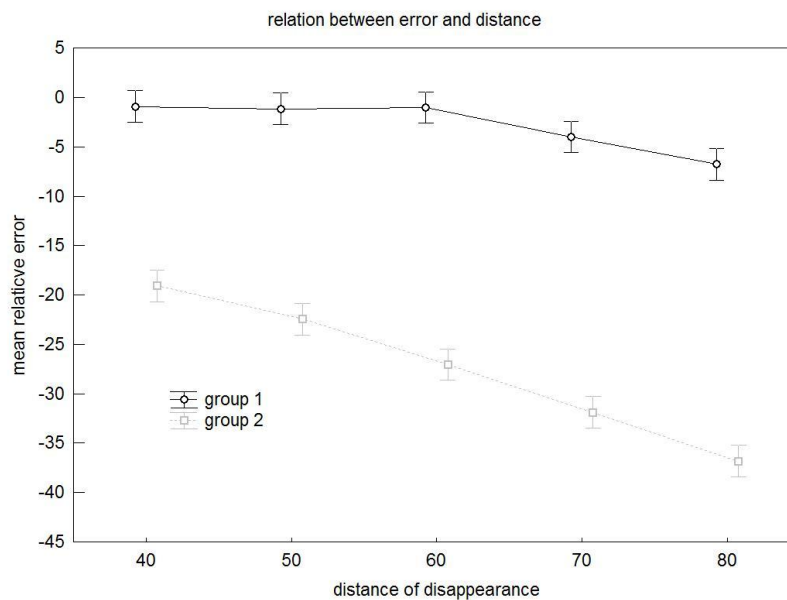


Figure 4: Error according to distance for both groups.

2.2.3 Analysis of performance during the training phase

Since the analysis allowed us to distinguish two perceptual profiles during the experimental sessions, the next step was to determine whether this distinction was already present during the training phase. The mean error obtained in the last ten trials of the closed-loop condition subtracted from the mean error obtained in the last ten trials of the open-loop condition is shown in Figure 5 as a function of the relative error during the 10 last trials of the closed-loop condition. Thus, the Y position of each point on the graph shows the error generated by the disappearance of vehicle *Cb*. The farther away the points are from the X axis, the higher this error is. The ellipses define the confidence interval around the mean values for each of the two groups identified above. Thus, this clustering analysis clearly shows that Groups 1 and 2, as identified from the HAC, exhibited distinct behaviors as early as the training phase. Furthermore, in order to characterize any change in performance during the training session for each participant, we calculated linear regressions applied to the series of performance index (this index allows to compare errors produced at different distances). Slope and intercept from these regressions for both groups and each individual are presented in the Table 2. A positive slope characterizes an improvement, a negative slope for a decrease, while nil slopes are obtained when performance does not evolve during the training session.

	Group 1							Group 2						
	Slope							Slope						
	1,400							0,048						
	intercept							intercept						
	67,484							54,17						
Slope	0,655	1,882	0,597	1,445	2,277	0,97	1,978	0,32	-0,198	2,725	-1,27	-1,395	0,471	-0,314
Intercept	82,612	54,628	74,044	66,578	55,358	74,831	64,333	57,598	43,673	12,895	88,478	103,12	26,787	46,644

Table 2 : slope and intercept of linear regression for both groups and each individual based on the index of performance.

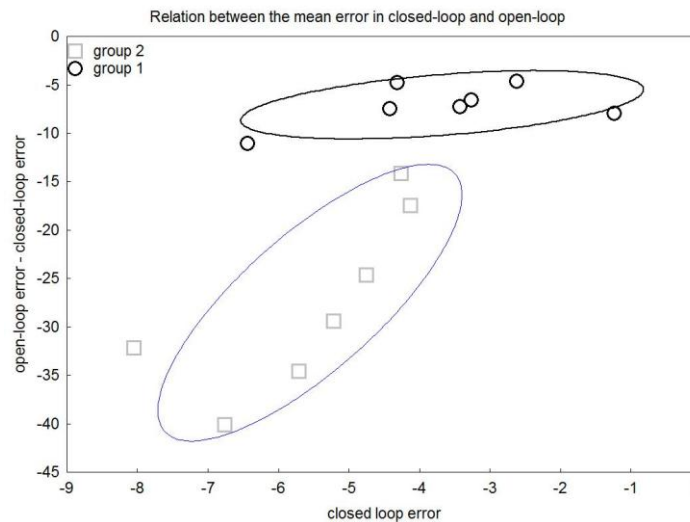


Figure 5: the x axis points represent the mean relative error of the last ten trials of the first familiarization phase (closed-loop). The y axis points represent the mean relative error obtained during the last ten trials of the second familiarization phase (open-loop) from which was subtracted the mean relative error of the last ten trials of the closed-loop phase. 95% Confidence ellipses were drawn for each group.

We then investigated whether the difference in performance between the two groups existed as early as the first trial of the training session. Figure 6 represents the evolution of the index of performance across trials of the open-loop familiarization phase.

Evolution of the index of performance during the familiarization phase

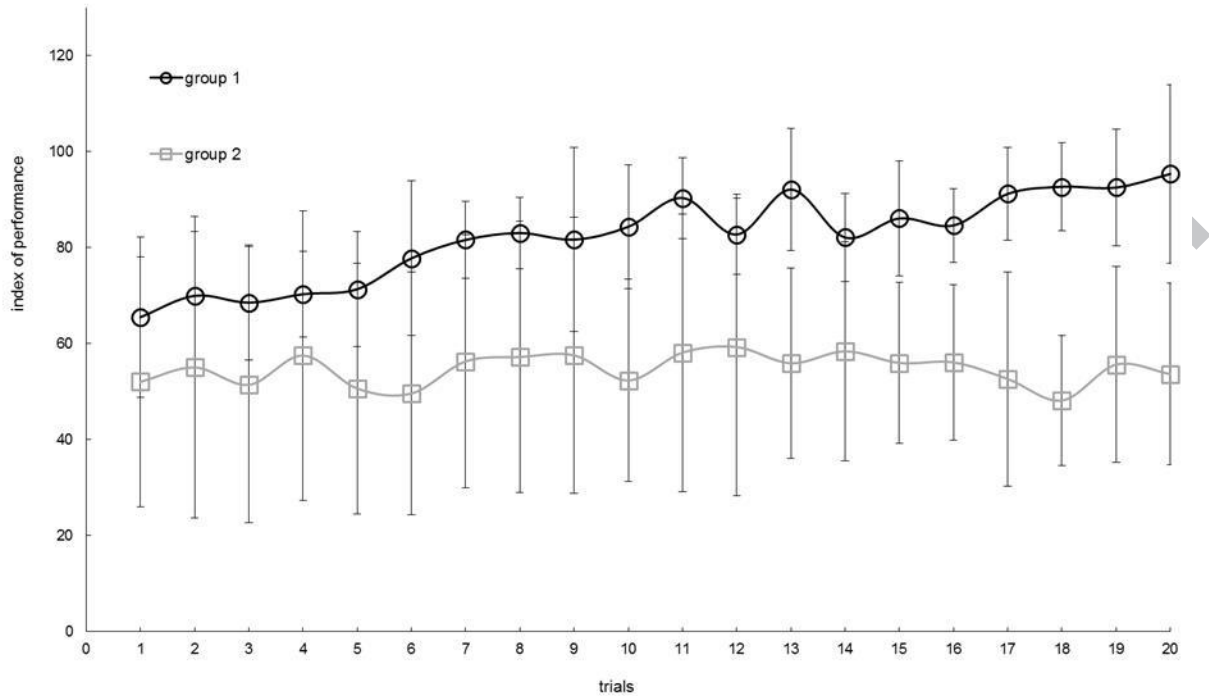


Figure 6: Index of performance of the twenty trials of open-loop familiarization phase for group 1 and group 2. Index of performance was calculated as follows: $(\text{Perceived distance}) * 100 / (\text{Distance of disappearance of Cb})$.

Figure 6 shows an offset between the two groups of 13.47% of the index of performance as early as the first trial. It also shows that the performance of participants in Group 2 tends to remain stable, while performance in Group 1 shows a sharp improvement of 29.54% during this familiarization phase. The final scoring gap between the two groups was 41.7%.

T-test for independent samples on the level of experience with VR systems revealed an higher expertise in group 1 than in group 2 $t(12) = -5.2, p < 0.001$ ($p < 0.001$), with a mean level of 0.86 and a standard deviation of 1.07 for group 1 and a mean level of 0.43 and a standard deviation of 0.79 for group 2.

2.3 Discussion

The aim of this experiment was first, to determine whether egocentric distance perception in virtual environments depends on two depth cues, namely stereoscopic vision and motion parallax, and second, to determine the effect of inter-individual differences. The results of this study highlight two distinct types of participant perceptual behaviors but we could not reveal any significant effect related to the different viewing conditions. These aspects will be discussed below.

2.3.1 Influence of stereoscopy and parallax

At first glance, it may seem surprising that participants did not notice any difference according to whether parallax and stereoscopy were present or not, but this is likely because of the fact that the cabin, representing the interior of the car, was always simulated with 3D parallax and stereoscopy, making the effects of these viewing conditions on the external scene less perceptible.

The analyses did not reveal any significant effect of condition on the perception of egocentric distance. Our results on the stereoscopic condition are consistent with several previous studies that have found no significant difference between distance estimates made in a binocular and in a monocular viewing condition in a real environment [13, 42], or made in a monoscopic as compared to a stereoscopic viewing condition, at least for long distances [13, 27]. However, contrasting results have been found in other studies [25, 26], especially for shorter distances (respectively 1-2.8m and 70% of the participant's maximum reach). Regarding the influence of motion parallax, studies have reached conflicting results: Jones, et al. [34] and Luo, et al. [26] found no influence of motion parallax on distance perception, while McCandless, et al. [43] and Creem-Regehr et al. [42] found that failure to include parallax leads to an underestimation of distances. Philbeck and Loomis [44] considered that motion parallax is a weak depth cue beyond 2 meters. In view of the size of the sample tested it is difficult to draw conclusions on the non-significance of the effect of the visualization conditions, at least for the tested distances. In order to confirm these results, we tested their possible effects on the perceived distance in the second experiment.

However, sample size allowed to test for large effect sizes with a test power of $\beta = 0.19$ (with $\alpha=0.05$ and a conservative expected size effect of 0.07 slightly higher than medium), but the present sample size ($n=14$) and power are not sufficient to detect significant differences with medium or small effect sizes.

2.3.2 *Inter-individual variability*

We found an overall underestimation of egocentric distances, which is consistent with most of the studies on the topic [9, 42]. However, closer examination revealed that participants could be divided into two groups of similar sizes based on a clear difference in their ability to estimate the distance to the target vehicle. One group significantly underestimated distance, as already reported in the literature, whereas the other group accurately estimated distance. Obviously, this finding is of great importance, casting doubt on most of the conclusions reached so far concerning distance perception in VR. Here, we can eliminate any suspicion that the difference in behavior between the two groups was due to the fact that group 2 (who underestimated distance) did not have a training phase long enough to stabilize their behavior. Had this been the case, their performance would have improved and finally stabilized in the subsequent phases. Rather, our results show Group 1 to perform relatively better in terms of distance estimation error from the very first trial on, and their performance improves during training. As highlighted in Fig. 3, this suggests that it may be possible to predict the category (and thus the future performance) of a participant simply from the data collected during the familiarization phase, since the two groups clearly perform differently as early as this initial phase. The predictive aspect of this preliminary phase is of crucial importance, identifying those individuals unable to perceive distances in VR as well as in the real world (or at least, as well as people from the other group). Of course, this important result needs to be confirmed and generalized with other tasks involving distance perception in VR systems. The discovery of this group effect was unexpected, so determining precisely the origin of the differences between these two groups of participants is beyond the scope of this study. However, we can formulate certain hypotheses, which merit further investigation.

We can hypothesize that these results indicate the use of different perceptual strategies of differing degrees of efficiency, those implemented by Group 1 being more accurate. We use here the term perceptual strategy to designate the privileged use of one information relative to others and / or the different weight given to this information. As the two groups are not distinguished by different use of depth indices manipulated in this experiment, it is quite possible that there is a difference in how they use information that is available but is not manipulated here such as linear perspective, relative size, or aerial perspective. These two distinct profiles might stem from the use of different perceptual processes, depending on the individual and the distance at which the estimation is made. The two strategies might implement processes with specific characteristics that might differ in terms of precision.

Greater experience of VR devices in group 1 would indicate that it is important to control this parameter for all studies on human behavior in VEs. Furthermore, this result could mean that the performance in distance estimation in VEs may get better with practice. We can also speculate as to the efficiency of learning processes. Analysis of the results clearly shows that the distinction between our two groups of participants appears early during the familiarization phase. During the open-loop phase, the performance of Group 2 tended to remain steady (which probably indicates that they were not learning how to improve their performance), while Group 1 were able to improve their performance throughout this phase. This finding clearly shows that the participants committing fewer errors during the experiment were those whose performance improved even without visual feedback (during the second part of the familiarization phase).

It can be concluded from the results of the first experiment that focusing solely on the mean error of all participants in a distance estimation task is not appropriate to describe the perceptual phenomenon.

Individual, or at least group, analysis seems to be a more efficient way to take into account inter-individual differences in performance. Our second conclusion concerns the influence of stereoscopic vision and motion parallax, under our conditions. The observations so far reported only relate to the ability to perceive long distances, probably too long for information provided by stereopsis or motion

parallax to be used. In order to confirm the hypothesis about the potential influence of interactive conditions on distance perception in VR, the task must be replicated with shorter distances, in order to treat long and short distances as a continuum. We therefore conducted a second experiment similar to experiment 1 with a range of distances widened to include short ones.

3. Experiment 2

3.1 Methods

3.1.1 Participants

Data collected from 14 participants (6 women and 8 men) are presented here. These participants, aged 23-35 years (mean 27 ± 3) had held a driving license for over 5 years and had normal or corrected to normal vision. Driving expertise was measured in terms of driving time per week. As in experiment 1, participants were tested for binocular vision (RandotTest[®]). They completed a questionnaire for sensitivity to motion sickness (Reason and Brand Motion Sickness Susceptibility Questionnaire (MSSQ)[40,41], In a case a participant replied that he/she felt sick or nauseated frequently in cars over the last ten years, he/she was then excluded from the study (one person was excluded). They all signed informed consent forms informing them of the conditions of the experiment (except for the presence or absence of the two depth cues), their right of withdrawal and the obligation not to drive for two hours after the session, in accordance with the Helsinki convention. The level of experience with VR systems was rated by the participants on a scale ranging from 0: none to 3. The protocol was approved by the institutional review board of the Institute of Movement Sciences. Data were analyzed anonymously. None of these participants had taken part in the first experiment, and thus all were completely naïve regarding the objectives of the experiment. Moreover, studying the same subjects as for the previous

experiment would lead to the same distinction of two distinct profiles, and we wanted to confirm these significantly different behaviors in this second experiment with a new sample of participants.

3.1.2 Task and experimental device

The task was strictly identical to that of experiment 1, with the exception of the range of distances tested. In this second experiment, the target disappeared at a distance of 5, 10, 20, 40 or 80 m. Conditions CC, PC, SC and TC were tested in the same way, and participants performed a training session identical to that of experiment 1. The same experimental device was used.

3.2 Results

Once again, as in experiment 1, none of the participants noticed any difference according to whether the two depth cues were absent or present.

3.2.1 Analysis of relative errors

The average relative error (distance between C_b and C_a) for all conditions and all distances was -8.96 m (overall underestimation), with a standard deviation of 14.11 m. A Lilliefors normality test performed on the mean relative error for each participant in each condition showed that data followed a normal distribution. A 2 stereoscopy condition * 2 parallax condition * 5 distances repeated measures ANOVA was performed. Once again, this analysis revealed a lack of significant effect of condition on performance ($F(1, 13) = 0.03$, $p = 0.88$ for stereoscopic conditions and $F(1, 13) = 1.11$, $p = 0.31$ for parallax conditions), and no interaction between distance and conditions ($F(4, 52) = 0.18$, $p = 0.95$), but

revealed a significant effect of distance on performance ($F(4, 52) = 39.08, p < 0.001$). The mean errors as a function of distance and condition are presented in figure 7.

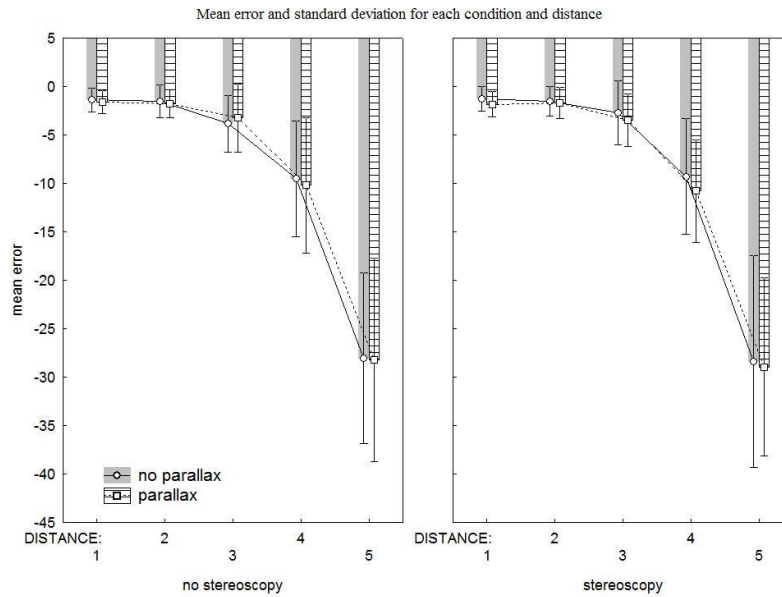


Figure 7: mean errors as a function of distance and condition.

Post hoc Tukey's test revealed that mean relative error was not significantly different between the three shorter distances: 5 m, 10 m, 20 m. It also revealed that mean relative error in the 40m and 80m conditions was significantly different from that in all other distance conditions ($P < 0.001$ for all cases).

3.2.2 Inter-individual variability

As in experiment 1, participants' error profiles differed greatly. We therefore performed analyses to assess whether participants fell into distinct categories. A hierarchical ascending classification (HAC) by Ward's criterion (figure 8) showed that our sample could be divided into two distinct categories based on relative error: Group 1 composed of 7 participants (5 men and 2 women) and Group 2 composed of 7 participants (3 men and 4 women). Participants from Group 1 achieved an average error of $-3.713 \text{ m} \pm 9.041$, against $-14.204 \text{ m} \pm 16.172$ for Group 2. Individual data are presented in table 3.

	Group 1							Group 2						
	mean							mean						
	-3.73							-14.20						
	SD							SD						
	9.04							16.17						
Mean	-10.64	-6.65	+1.97	-3.86	+3.21	-3.01	-7.01	-11.62	-10.08	-22.05	-13.28	-14.75	-14.50	-13.15
SD	8.99	8.17	7.27	5.22	7.45	6.77	9.92	13.99	13.75	22.41	17.50	16.36	10.35	13.79

Table 3: Relative Error and Standard Deviation for both groups and each participants.

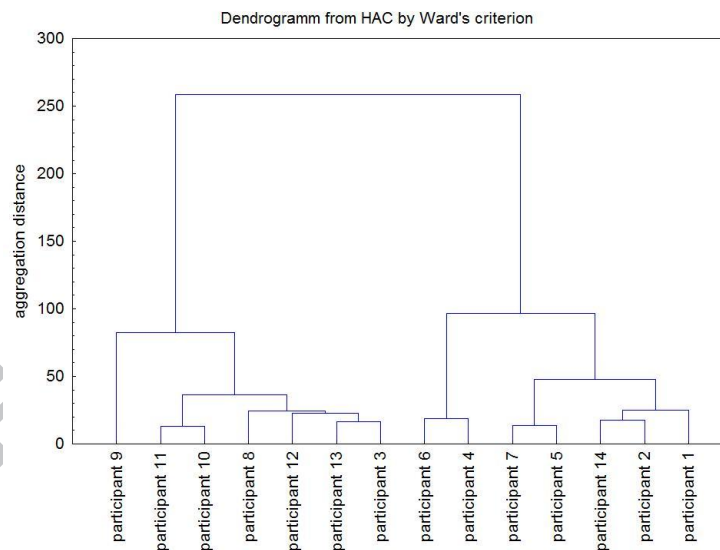


Figure 8: Hierarchical ascending classification by Ward's criterion based on RE (Euclidean distance).

A 2 groups x 2 stereoscopic conditions x 2 parallax conditions x 5 distances repeated measures ANOVA was performed. As in experiment 1, it yielded a significant effect of group ($F(1, 12) = 52.07, p < 0.001$),

a significant effect of distance ($F(4, 48)=37.71, p<0.001$), and no significant effect of condition ($F(1, 12)=0.03, p=0.87$ for stereoscopic conditions and $F(1, 12)=1.04, p=0.33$ for parallax conditions).

Interaction effects were tested, showing no significant interaction between condition and distance ($F(4, 48)=0.17, p=0.95$), no significant interaction between condition and group ($F(1, 12)=0.16, p=0.70$), and a significant interaction between distance and group ($F(4, 48)=38.39, p<0.001$). Post hoc Tukey's tests revealed for Group 1 no significant difference in mean relative error for 5m, 10m, 20m, and 40m. For Group 2, the mean relative error for 20m, 40m, 80m was significantly different from that for all other distances ($P<0.001$ for all cases), showing that distance had a greater influence on performance for this group.

A 2 groups * 2 stereoscopy condition * 2 parallax condition * 5 distances repeated measures ANOVA was performed on standard deviation. This analysis revealed no significant effect of condition on variability ($F(1, 12)=1.59, p=0.23$ for stereoscopic conditions and $F(1, 12)=0.08, p=0.78$ for parallax conditions), no significant effect of groups ($F(1, 12)=1.94, p=0.19$), but a significant effect of distance ($F(4, 48)=86.53, p<0.001$) showing that variability increases when the distance to be estimated increases.

T-tests for independent samples show no significant effect of driving expertise $t(12)=0.18, p=0.86$ and a significant effect of the level of experience with VR systems $t(12)=3.98, p<0.001$ with a mean level for group 1 of 0.86 with a standard deviation of 0.90 and a mean level for group 2 of 0.71 with a standard deviation of 0.76.

3.2.3 Analysis of the familiarization phase

As in the first experiment, the two groups can be distinguished as early as the familiarization phase. The mean error obtained in the last ten trials of the closed-loop condition subtracted from the mean error obtained in the last ten trials of the open-loop condition is shown in Figure 9 as a function of the relative error during the 10 last trials of the closed-loop condition. Thus, the Y position of each point on the

graph shows the error generated by the disappearance of vehicle Cb. The farther away the points are from the X axis, the higher this error is. The ellipses define the confidence interval around the mean values for each of the two groups identified above. Thus, this clustering analysis clearly shows that Groups 1 and 2, as identified from the HAC, exhibited distinct behaviors as early as the training phase.

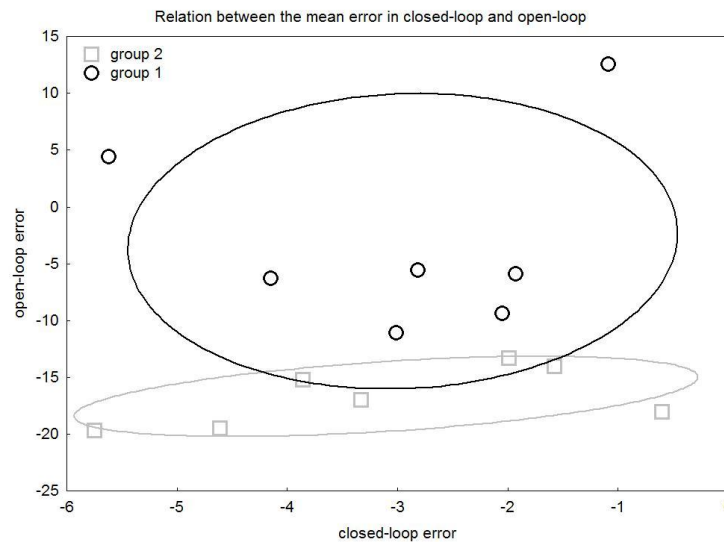


Figure 9: the x axis representst the mean relative error of the last ten trials of the first familiarization phase (closed-loop). The y axis represents the mean relative error obtained during the last ten trials of the second familiarization phase (open-loop) from which was subtracted the mean relative error of the last ten trials of the closed-loop phase. 95% Confidence ellipses were drawn for each group.

Figure 10 shows, for each of these two groups of participants, an offset between the two groups of 6.97% of the index of performance on the first trial. Again, we can see that the performance of participants from Group 2 tends to remain steady (slope of the regression close to zero or even negative), while performance in Group 1 shows a sharp improvement during this familiarization phase positive slope). As for experiment 1, slope and intercept of linear regression for both groups and each individual are presented in Table 4.

	Group 1							Group 2						
Slope	1,100							-0,213						
Intercept	68,153							54,894						
Slope	0,419	0,546	1	0,317	4.1	0,7478	1.21	0,352	0,940	-0,52	0,261	-0,17	-1,025	-1,329
Intercept	59,325	60,853	112	78,464	32,785	74,414	59,231	32,791	52,048	45,304	59,754	56,92	66,4	71,038

Table 4: Slope and intercept of linear regression for both groups and each individual based on the index of performance.

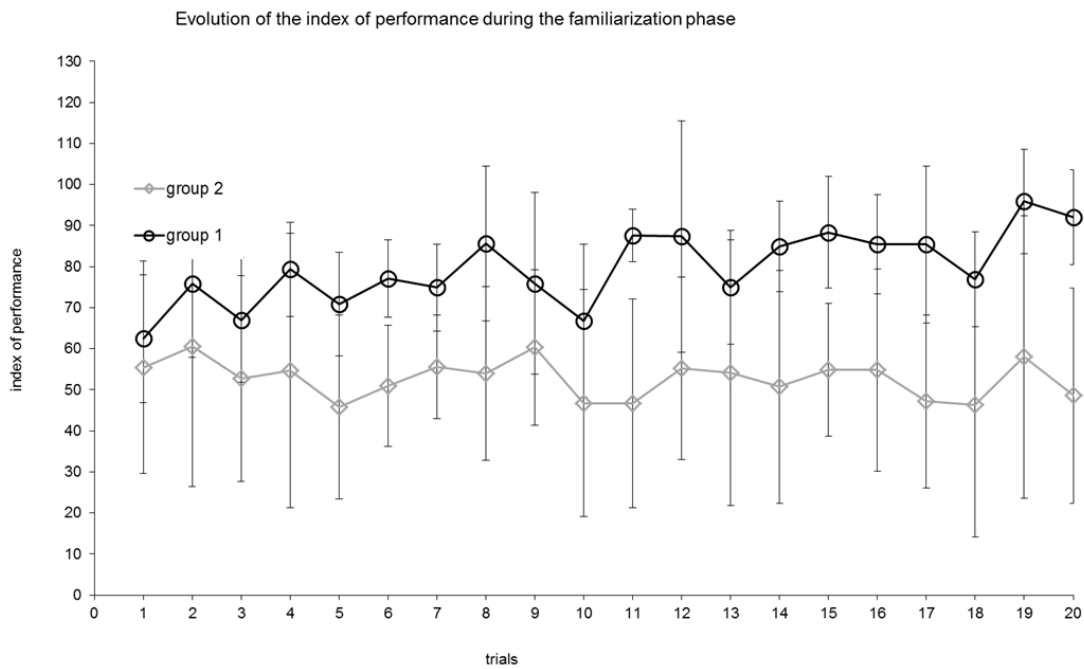


Figure 10: Index of performance of the twenty trials of open-loop familiarization phase for group 1 and group 2. Index of performance was calculated as follows: $(\text{Perceived distance}) * 100 / (\text{Distance of disappearance of Cb})$

3.3 Discussion

The aim of this second experiment was, first, to determine whether the lack of significant effect of the presence or absence of parallax and stereoscopy on participants' performance was confirmed for shorter distance estimation and, second, to determine the effect of inter-individual differences when a wider range of distances is considered.

3.3.1 *Influence of stereoscopy and parallax*

Concerning the effect of visualization conditions, although tested over a wider range of distances (including short distances), the analysis did not reveal a significant effect of the presence or absence of parallax and stereoscopy on participants' performance. These results are consistent with studies considering that these cues are exploitable exclusively in very near space [15, 24, 47]. Nevertheless, the depth cues in the two experiments reported here, while accessible to participants, may not be taken into account in the final perception, at least under the conditions of our study. The resulting perception may therefore be the product of additional sources of information, considered more reliable by the nervous system, such as ground texture [48], height in the visual field [49] or personal variables [50-52]. In line with findings by Ee and al. [53] and by Jacobs [54], this could be due to nonlinear behavior by the visual system: information provided by stereoscopy and head motion parallax are not taken into account because they deviate too much from other available information. However, as for experiment 1, sample size ($n=14$) allowed to test for large effect sizes with a test power of $\beta = 0.19$ (with $\alpha=0.05$ and a conservative expected size effect of 0.07 slightly higher than medium), but the present sample size and power are not sufficient to detect significant differences with medium or small effect sizes.

3.3.2 *Inter-individual variability*

Once again, data analysis revealed that participants could be divided into two groups, of equal numbers, on the basis of a clear difference in their ability to estimate the distance to the target vehicle. One group's behavior was similar to that generally described in the literature, with a significant underestimation of distances, while the other group seemed to correctly estimate distances.

As discussed above, these idiosyncratic patterns are found not only for long distances but also over a wide range of distances. To better understand this finding, it would be interesting to investigate to what extent it stems from the virtuality of the situation and from the task of driving (for instance by testing different tasks). These issues will be the subject of a future study.

Analysis of the results clearly shows that, as in experiment 1, the distinction between the two groups of participants appears as early as the familiarization phase. As in experiment 1, the evolution of the response patterns of the two groups of participants is clearly distinguishable: Group 2's performance tends to remain steady, while Group 1's performance improves throughout this phase. Obtaining the same result in both experiments confirms the familiarization phase as a strong predictor of participant behavior, suggesting its considerable importance for all studies using virtual reality.

4. **General discussion and conclusion**

This study was aimed at understanding why humans underestimate egocentric distances while immersed in a virtual environment. Two ranges of distance were tested. Two main results emerged from both experiments: first, under the conditions tested here (driving task in a static simulator) the inclusion of stereoscopic vision and/or motion parallax seems not to have significantly affected distance perception. Second, there were strong inter-individual differences in distance perception: some participants as expected from the literature, clearly underestimated distances, while others quite accurately estimated a wide range of distances.

Concerning inter-individual variability, various conclusions can be drawn from the fact that we were able to identify two very distinct behaviors among our sample, one largely identical to the behavior reported in real world studies, and the other involving major underestimation of distance. This may partially explain the numerous contradictory results in the literature. Analyzing the mean performance of all test subjects can yield conclusions that are only correct for some, and not necessarily a majority of, participants. In our case, regardless of inter-individual differences, analyzing a set of individuals including both subjects who underestimate and subjects who correctly estimate distance will inevitably lead to a generalization of underestimation.

In the field of spatial perception, however, very few studies have been devoted to inter-individual differences. One question that needs to be addressed is that of the factors potentially responsible for this variability.

Murgia and Sharkey [55] investigated whether degree of experience with CAVEs influenced distance perception, but only found a marginal significance. In our study, greater experience of VR devices in group 1 confirms that it is important to control this parameter for all studies on human behavior in VEs and this result is consistent with an improvement of the spatial scale perception with the practice in VEs. This study emphasizes the need to take precautions when questioning the transferability in the real world of observations made in a driving simulator. In view of the high inter-individual variability, it seems preferable for the development of ADAS to test a significant number of participants who do not have the same level of expertise in the use of VR systems.

Finally, performance during phases of familiarization with the task appears to be predictive, to some extent, of behavior during the experimental phase, which has implications for all studies in VR. The participants who learned best, that is, those who improve their performance in the open-loop phase, are those who proved best at judging distance. This suggests the relevance of good-quality, controlled familiarization phases prior to any experiment conducted on a driving simulator. Furthermore, such phases can be used to select the "best" participants, in this case those whose perception during the virtual

simulation comes closest to real-life perception. This prior phase needs to give participants access to the same spatial information and to consist of a task very similar to the experimental task that will follow.

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Highlights

- Stereoscropy and parallax do not affect distance perception in driving simulation.
- Two participant profiles can be distinguished.
- Familiarization phase can be predictive of participants' perceptual behavior.

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