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Impact of visual immersion on perception of urban morphology and density in 3D city models

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Abstract—Urban information visualization is an essential tool for decision process in urban planning. Nowadays, more and more urban visualizations incorporate virtual 3D city scenes to better convey spatial and morphological information. On the other hand, the development of consumer grade VR devices as Head Mounted Displays (HMD) enable to visualize urban information with a greater degree of immersion. These new ways to render and display 3D city models may have a significant impact on the perception of urban morphology and, consequently, on the interpretation of the urban visualization. In this paper, we present a subjective experiment to evaluate the impact of visual immersion – field of view, stereoscopy and allocentric or egocentric representations – on the perception of urban morphology and density in 3D city models. Obtained results can be useful to improve urban visualization, but also to better understand perception, user behavior and navigation in 3D virtual environments.

Index Terms—3D city models, Perception, Urban visualization, Immersion, Head Mounted Display, Virtual reality.

1 INTRODUCTION

Urban information visualization is an essential tool for decision process in urban planning. Nowadays, more and more urban visualizations incorporate virtual 3D city scenes to better convey spatial and morphological information [1]. On the other hand, the development of consumer grade VR devices as Head Mounted Displays (HMD) enable to visualize urban information with a greater degree of immersion. These new ways to render and display 3D city models may have a significant impact on the perception of urban morphology and, consequently, on the interpretation of the urban visualization. In this paper, we propose to evaluate the impact of visual immersion — field of view, stereoscopy and allocentric or egocentric representations — on the perception of urban morphology and density in 3D city models. This study aims at linking the quality of the visualization and the perceived quality of the urban space, in the specific context of density visualization and evaluation.

The paper is organized as follows. Section 2 presents some relative works about urban density, perception of 3D models and impact of visual interfaces on user experience. Then, a subjective experiment about the impact of visual immersion on the perception of urban density and morphology is described in Section 3. The obtained results are presented and discussed in Section 4. Finally, conclusion and future works end the paper in Section 5.

2 RELATED WORKS

2.1 Urban density

In urban planning, density analysis is essential because of the constant augmentation of population and services in cities and its impact on the perception and appropriation by final users of their environment [2], [3]. Density is a complex notion based on different aspects as population and dwelling densities, land use intensity, coverage, building height and uniformity, spaciousness, etc [4]. Thus, the evaluation of density is not simple and, providing efficient

3D urban visualizations would be helpful for the various actors involved in urban planning. However, because urban density directly depends on urban form, it is important, prior to any visualization of density indicators in 3D city scenes, to qualify how morphology is perceived in 3D urban models.

2.2 Perception of 3D models

The perception of urban form of 3D city models can be influenced by the perception of depth, shape and distances in virtual environment, depending on rendering and display features, such as the field of view, the viewpoint, the stereoscopy and the realism.

First of all, several physiological and psychological factors are involved in the perception of depth [5]. Physiological factors are either binocular — e.g. accommodation, vergence, stereopsis (or binocular disparity) —, or monocular — e.g. motion parallax. All the psychological cues are monocular — e.g. retinal image size, linear and aerial perspectives, shadowing and shading. According to the visual interface and the quality of the rendering, the different cues could be more or less effective to perceive depth [5]. On monoscopic screens, mainly psychological cues are used to deduce depth information. On stereoscopic displays, two different images are conveyed to each eye, enabling depth perception thanks to stereopsis. However, stereoscopic devices create ocular and cognitive constraints (e.g. accommodation/vergence conflict) which can damage visual acuity and can lead to visual fatigue [6].

On the other hand, 3D city models enable users to modify their viewpoint, moving from egocentric to allocentric representations which can impact perception of space [7]. Moreover, in egocentric representation of virtual environments, distances are judged compressed [8]. The reasons of this effect are not very clear and different causes can interact, like the field of view of the display and the geometric field of view (field of view of the camera), the lack of realism of the model, etc [9], [10].

For all of these reasons, visual interfaces and visual immersion may influence the way morphology is perceived in 3D urban environments and therefore the way density is derived and evaluated.

2.3 Impact of visual interface on user experience

A few studies directly compared user experience and performance while using HMD and desktop. Robertson *et al.* compared user behavior and navigation between HMD (with head-tracking) and desktop [11]. They found that participants were faster with HMD: they adopted a more natural behavior by looking around more while they were moving and they spent less time stationary. Santos *et al.* compared user performance with HMD and desktop to navigate and catch objects in a game scenario [12]. They found that participants were faster and grabbed more objects while on desktop. However, this results could be biased by user experience: the paper showed that users who rarely played video games usually performed better with HMD. In terms of user experience, participants enjoyed both devices, but more users felt disoriented and sick in the HMD condition comparing to the desktop one. It could be due to technical limitations of the HMD (i.e. low resolution, narrow field of view, low contrasts, discomfort of the cables connecting HMD, etc.).

More recently, some studies focused also on the comparison between TV screen and HMD in terms of enjoyment, attention, presence, etc. [13], [14], [15] However, this work concerns entertainment applications and is more distant from our current questions.

3 EXPERIMENTAL DESIGN

We present here a subjective study about the perception of urban morphology and density for different visual immersion conditions:

- allocentric or egocentric representations;
- monoscopic desktop screen or stereoscopic HMD device.

This experiment was conducted in the University of Nantes.

3.1 Virtual urban environment and stimuli

The stimuli used in this experiment were extracted from a 3D city models of the city of Nantes¹ (France). Ten virtual urban scenes, homogeneous in terms of urban morphology, were manually selected to be assessed by the observers. The scenes are illustrated Figure 1.

The virtual scenes were viewed from two different viewpoints: allocentric or egocentric. In allocentric representation, observers could visualize the 3D city models from a bird's eye view and the urban scene of interest was highlighted in red as we can see Figure 1. In egocentric representation, observers were immersed in the scene in first person view and the urban scene of interest was delimited thanks to semi-transparent walls as we can see Figure 1.

1. c Nantes Metropole 2010

3.2 Experimental setup

For each scene, the two types of representation, allocentric or egocentric, was visualized on two different devices: desktop or HMD. The desktop screen used in this experiment was a DELL 2208WFPt with a 1680×1050 resolution and a 22 inch size. Observers were seated at a desk in front of the computer and used a keyboard and a mouse to interact with the application (see Figure 2a).

The HMD used in this experiment was the HTC Vive with one Vive controller to interact with the application. The viewport resolution of HTC Vive was 1200×1080 per eye and the viewing angle was around 110° in both horizontal and vertical directions. The orientation of the head was tracked with the Vive base stations. The observers were themselves seated comfortably in a turn-chair and were free to rotate the full 360 degrees (see Figure 2b).



(a) Desktop condition



(b) HMD condition

Fig. 2. Experimental setup.

The application was implemented on Unity 3D.

3.3 Navigation and interfaces

On desktop in egocentric representation, participants navigated in the 3D model with arrow keys and the mouse was used to control the camera. In egocentric representation with HMD, participants navigated with the pad of the Vive controller. The camera was controlled thanks to the head tracking.

In allocentric representation, observers could move along an ellipsoid orbit centered on the scene of interest (see Figure 3a). The orbit was initially located at an altitude of 220 meters and observers could zoom in and zoom out from 44 meters to 316 meters above the ground (see Figure 3). Participants could also change the orientation of the camera along the orbit. In desktop condition, observers used the right and left arrow keys to move along the orbit, and the up and down arrow keys to zoom in and out. In HMD,

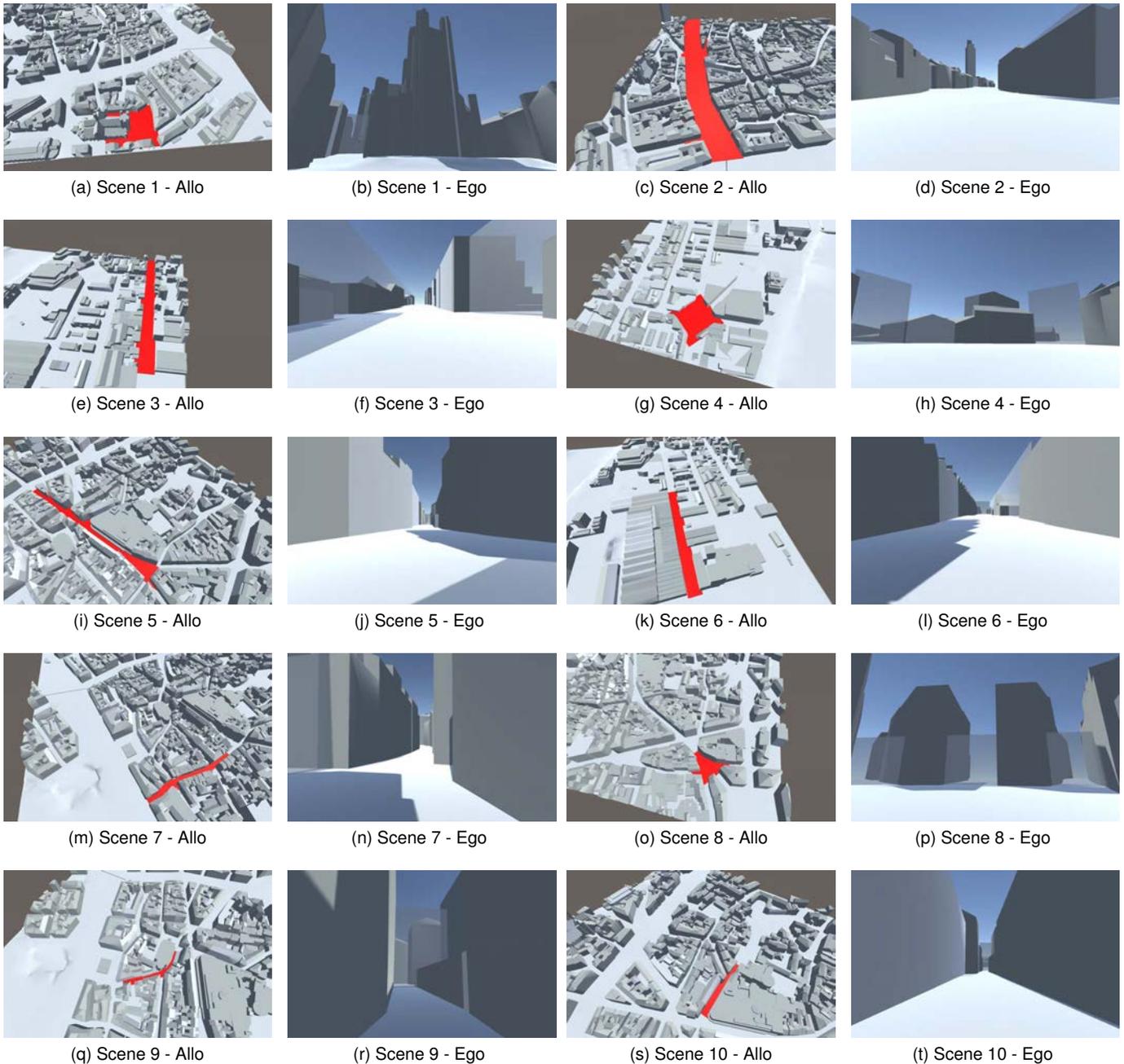


Fig. 1. Screenshots of the 10 urban scenes assessed during the experiment in allocentric (Allo) and egocentric (Ego) representations.

these actions were achieved with the trackpad of the Vive controller. The camera was still controlled with the mouse on desktop and thanks to the head tracking in HMD.

After the visualization of each scene, participants had to answer a questionnaire to evaluate urban morphology. To pause the immersion in the 3D model, users had to right click with the mouse or push the trigger, according to the used device. Then, they had to select, in a 2D menu, whether to continue navigation or to switch to the questionnaire interface. Finally, they had to answer the questionnaire displayed on the screen with the mouse or, in HMD, with the trackpad of the Vive controller.

3.4 Experimental protocol

The ten urban scenes were evaluated by each observer in four sessions corresponding to the four viewing conditions: allocentric viewpoint on desktop screen, egocentric viewpoint on desktop screen, allocentric viewpoint in HMD, egocentric viewpoint in HMD.

The order of the sessions were randomized for each observer but, in order to avoid visual fatigue, the two HMD sessions were never done successively. In each session, the ten scenes were also displayed and assessed in a random order.

After each urban scene, the participants had to evaluate their perception of the four following urban characteristics on a 5-point Likert scale:

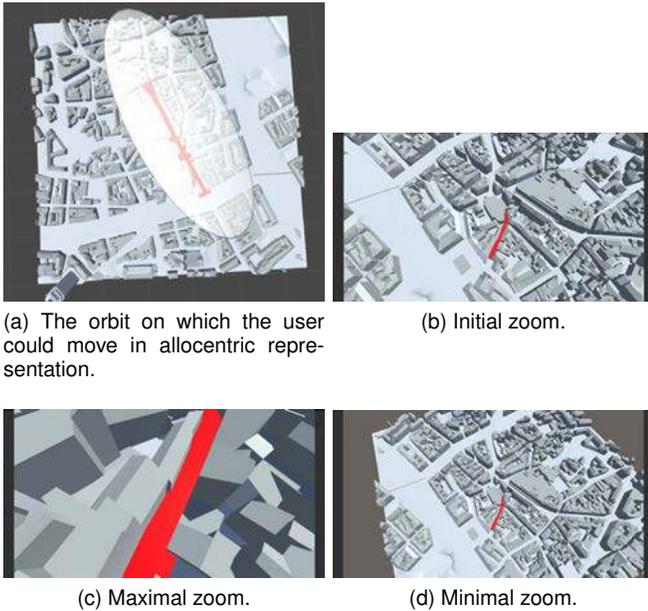


Fig. 3. Navigation and zoom in allocentric representation.

- Density (very low, low, medium, high, very high);
- Building height (very low, low, medium, high, very high);
- Ground space (very narrow, narrow, medium, large, very large);
- Building uniformity (not diverse, slightly diverse, medium, diverse, highly diverse).

After the four sessions, the participants had to fill in a questionnaire where they were asked to rank the four different viewing conditions in terms of:

- 1) facility to evaluate density;
- 2) facility to evaluate building height;
- 3) facility to evaluate ground space;
- 4) facility to evaluate building uniformity;
- 5) facility to perceive depth;
- 6) facility to understand urban morphology;
- 7) sense of presence in the urban space.

3.5 Participants

Twenty-three remunerated observers participated to this experiment. They were aged from 20 to 60 (most of them were students with different backgrounds). Before the experiment, participants were asked to sign a consent form and instructions were given.

4 RESULTS AND DISCUSSION

4.1 Impact of visual immersion on urban morphology

Each perceived urban characteristic — density, building height, ground space and building uniformity — can be seen as the dependent variable of a full factorial design where independent factors are:

- Viewpoint (V): allocentric or egocentric;
- Display (D): monoscopic screen or stereoscopic HMD.

Results on 5-point Likert scale were projected from 0 to 4.

Because of the non-normality of the residuals, the statistical analyses were done using Friedman test (i.e. non-parametric version of two-way ANOVA).

4.1.1 Density evaluation

The Friedman test shows that the null hypothesis cannot be rejected for both independent factors, i.e. Viewpoint ($\chi^2_V(1) = 0.15$, $p_V = 0.70$) and Display ($\chi^2_D(1) = 0.45$, $p_D = 0.50$).

Surprisingly, and contrary to our expectations, the evaluation of density in 3D city models does not seem to be affected by the viewing mode.

4.1.2 Building height evaluation

The Friedman test shows that the null hypothesis cannot be rejected for the factor Display ($\chi^2_D(1) = 0.011$, $p_D = 0.92$) but can be rejected for the factor Viewpoint ($\chi^2_V(1) = 45.53$, $p_V < 0.001$).

As illustrated by Figure 4, buildings were perceived higher in egocentric than in allocentric representations. Relief tends to be perceived as flattened from a bird's eye point of view.

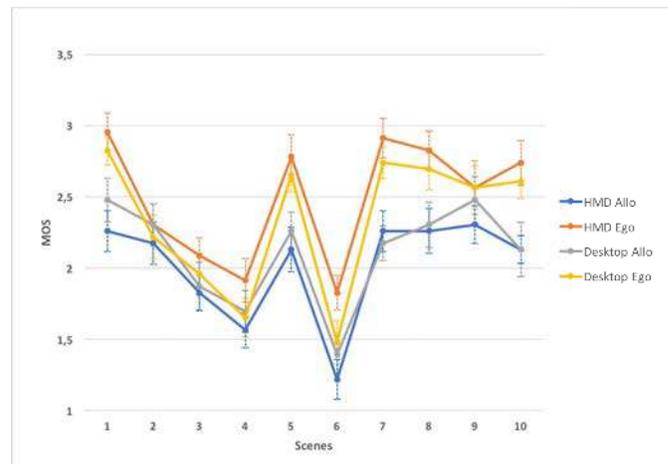


Fig. 4. Mean Opinion Scores (MOS) for building height evaluation (error bars correspond to standard errors).

In order to explore the cross effects between factors, a pairwise comparison between all the four viewing modes was performed thanks to the non-parametric Wilcoxon rank sum test (see Table 1). Results show that the factor Viewpoint has a significant effect on building height perception for both desktop and HMD but, as can be seen on Figure 4, the effect seems stronger in HMD. It could be explained by the fact that stereoscopy, as well as a large field of view and the visualization of the buildings at scale 1, may strengthen the impression of height in egocentric representations with HMD.

4.1.3 Ground space evaluation

The Friedman test shows that the null hypothesis can be rejected both for the factor Viewpoint ($\chi^2_V(1) = 7.68$, $p_V = 0.006$) and the factor Display ($\chi^2_D(1) = 11.13$, $p_D < 0.001$).

Viewing modes		Z value	p value
Desktop Allo	Desktop Ego	-3.24	0.0012
Desktop Allo	HMD Allo	-1.49	0.14
Desktop Allo	HMD Ego	4.78	< 0.001
Desktop Ego	HMD Allo	-4.77	< 0.001
Desktop Ego	HMD Ego	1.60	0.11
HMD Allo	HMD Ego	-6.31	< 0.001

TABLE 1
Pairwise comparison for building height evaluation.

Viewing modes		Z value	p value
Desktop Allo	Desktop Ego	-1.01	0.31
Desktop Allo	HMD Allo	1.55	0.12
Desktop Allo	HMD Ego	4.21	< 0.001
Desktop Ego	HMD Allo	0.42	0.67
Desktop Ego	HMD Ego	3.16	0.0016
HMD Allo	HMD Ego	-2.91	0.0036

TABLE 2
Pairwise comparison for ground space evaluation

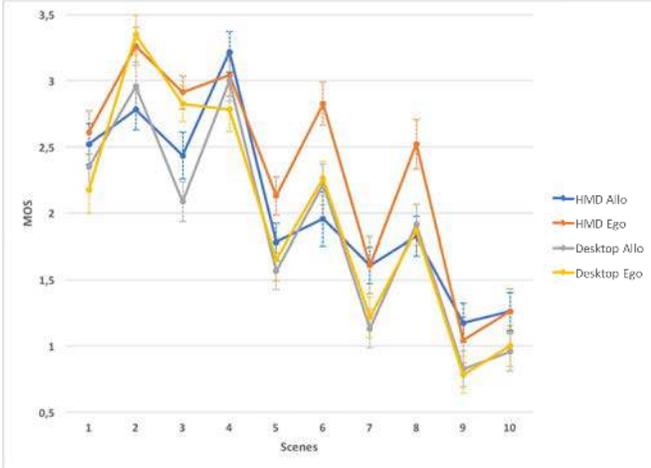


Fig. 5. Mean Opinion Scores (MOS) for ground space evaluation (error bars correspond to standard errors).

Figure 5 shows that observers perceived the ground space larger in egocentric representations and with HMD.

In order to explore the cross effects between factors, a pairwise comparison between all the four viewing modes was performed thanks to the non-parametric Wilcoxon rank sum test (see Table 2). Results show that the viewpoint has a significant effect only in HMD and that the display has a significant effect only for egocentric representation. Indeed, only pairs with HMD Egocentric viewing mode are significantly different, with an overestimation of the ground space (Figure 5). This result disputes previous results which showed that distances are perceived as compressed in egocentric representations of virtual environments [8]. It may be explained by the fact that a larger field of view in HMD enables, in first person viewpoint, the perception of urban environment in peripheral vision, leading to an impression of higher spaciousness.

4.1.4 Building uniformity evaluation

The Friedman test shows that the null hypothesis cannot be rejected for both independent factors ($\chi^2_V(1) = 1.57$, $p_V = 0.21$ and $\chi^2_D(1) = 3.44$, $p_D = 0.064$). Visual immersion does not seem to impact building uniformity perception. The standard deviation computed on mean opinion scores for each scene was quite low (0.30) comparing to other perceptual characteristics; thus, we can assume that the models had not enough visual cues (e.g. building textures) to evaluate uniformity.

4.2 Correlation between perceptual urban characteristics

We investigate here if some correlations exist between the evaluation of density, building height, ground space and building uniformity. Table 3 shows the Pearson and Spearman correlation coefficients for each pair of perceptual characteristics.

Viewing modes		R	ρ
Density	Building height	0.64**	0.62**
Density	Ground space	-0.87**	-0.87**
Density	Uniformity	-0.080	-0.053
Building height	Ground space	-0.37*	-0.37*
Building height	Uniformity	0.093	0.076
Ground space	Uniformity	0.30	0.26

TABLE 3
Pearson (R) and Spearman (ρ) correlation coefficients between perceptual urban characteristics (* $p < .05$; ** $p < .001$). The correlation coefficients were computed on mean opinion scores ($N_{data} = N_{scenes} \times N_{modes} = 40$).

Results show, as expected, a moderate positive correlation between density and building height and a strong negative correlation between density and ground space. They also exhibit a low, but coherent, negative correlation between building height and ground space.

Contrary to what it was shown *in situ* or in natural pictures [3], [16], no correlation has been found between building uniformity perception and density. It may be due to the absence of details on the 3D city models and, consequently, the difficulty for participants to evaluate uniformity.

4.3 Observers preferences

We present here the results of the final questionnaire where participants had to rank the four viewing modes. The answers of two participants, who did not understand well the instructions, were not integrated in the analysis.

Statistical analyses, computed with Friedman test, show that a significant effect of viewing mode on user ranking except for the evaluation of density and ground space (see Table 4). More particularly, egocentric view in HMD was logically preferred to evaluate height and depth as well as to understand urban morphology, whereas allocentric representations on desktop screen obtained the lowest scores (see Figure 6). Participants found difficult to assess building uniformity on egocentric representations displayed on desktop

screen (see Figure 6); probably because of the narrow field of view limits the possibility for observers to compare building shape in a urban scene from a single viewpoint. Finally, participants felt more immersed in HMD and in egocentric viewing modes.

A lot of participants reported a disorientation feeling using allocentric viewpoint with HMD. It may be due to the choice of the interactions (navigation and camera rotation on a fixed orbit) and the absence of reference point.

Dependent variable	$\chi^2(3)$	p value
Facility to assess density	1.17	0.76
Facility to assess building height	27.51	< 0.001
Facility to assess ground space	5.57	0.13
Facility to assess building uniformity	10.89	0.012
Facility to perceive depth	11.97	0.0075
Facility to understand urban morphology	15.57	0.0014
Sense of presence in urban space	29.51	< 0.001

TABLE 4
Results of Friedman test for all dependent variables with one independent factor (Viewing mode) with 4 levels

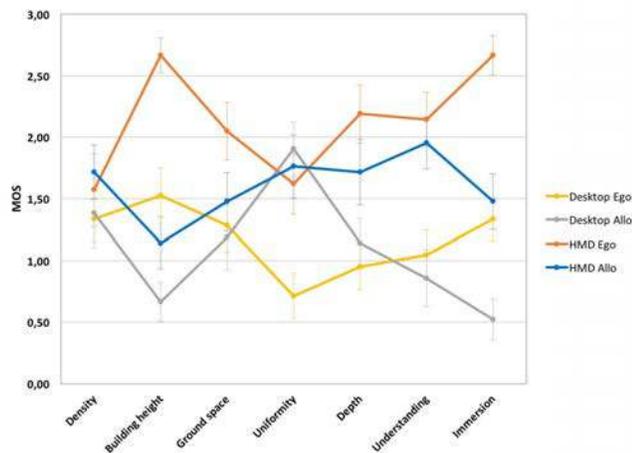


Fig. 6. Mean Opinion Scores (MOS) for viewing condition preferences.

4.4 General discussion

The impact of visual immersion on urban morphology and density perception was evaluated through a subjective experiment where participants had to evaluate urban perceptual characteristics for four different viewing modes, grouped in two factors Viewpoint and Display comprising two levels, respectively Allocentric / Egocentric and Desktop / HMD. We have found that building height was significantly overestimated whatever the display in egocentric representation and that ground space was significantly assessed as larger in HMD egocentric viewing mode. Moreover, subjective results show a moderate positive correlation between density and building height perception and a strong negative correlation between density and ground space perception. Nevertheless, they do not exhibit an impact of visual immersion on density assessment.

Here are some attempts to explain this latter result, rather unexpected. We know that *in situ* people base their judgment on building height and ground space to evaluate density. It turns out that visual immersion effects on urban morphology perception can offset themselves, while the combination of building height and ground space perception in density evaluation. Indeed, at least for HMD egocentric viewing mode, building are perceived higher but, at the same time, ground space is perceived larger than with the other modes. Considering the sign of the correlations between building height, ground space and density, it could cancel the differences on density evaluation between egocentric viewpoint in HMD and other viewing modes. However, this explanation cannot be valid for desktop display because building are also perceived taller with egocentric viewpoint but ground space is not perceived larger. We could assume that density is a complex and abstract notion based on different urban perceptual characteristics and that correlations between density, building height and ground space are not necessarily direct.

We could also potentially expect that allocentric representations were preferred by participants to assess density by comparison with other areas of the city, but no significant difference have been found between the viewing modes. On the contrary, observers voiced their preference to egocentric view with HMD to assess building height and ground space. These results can be also explained by the fact that density evaluation is based on the combination of a substantial number of urban characteristics, which should be still determined in 3D city models. In addition, these characteristics can differ from virtual environments to reality. Indeed, we have shown that building uniformity was not correlated with density perception in 3D city models without texture whereas it is the case *in situ* or on natural pictures [16].

The main results of this study is useful both for the virtual reality community — to better understand the impact of visual immersion on shape and morphology perception, which can impact user behavior and navigation [11], [12] — and for the field of urban information visualization. In this sense, the results tend to prove that visual immersion and visual interfaces can influence the way urban morphology is perceived. Consequently, when urban indicators and information are added to the 3D city models, the viewing mode can affect how this new information is interpreted regarding to the form and the physical characteristics of the studied urban area. We can recommend either to adjust the way urban data are visualized in the 3D city models according to the viewing mode, or to propose and advise to users to experiment all of the viewing modes.

In the near future, we plan to confront the subjective answers to objective indicators of urban scene physical morphology, in order to recommend some viewing modes tailored to the provided and displayed urban information. A deeper analysis of user behavior, as attentional processes from head and eye tracking, for the different viewing modes could also be useful to interpret the results obtained here, but also but also to provide valuable insights over the user performance in navigation and other tasks related to shape perception in virtual reality.

5 CONCLUSION

The recent use of 3D city models in urban planning process and the development of consumer grade VR devices raise new questions about the impact of viewing modes and visual immersion on the evaluation of urban characteristics, as morphology and density, from these 3D urban visualizations. To address these questions, we set up an experiment where participants had to evaluate density, building height, ground space and building uniformity of 10 virtual urban scenes of a 3D city model for four viewing conditions: allocentric viewpoint on desktop screen, egocentric viewpoint on desktop screen, allocentric viewpoint in HMD, egocentric viewpoint in HMD. Results mainly show a significant impact of visual immersion on the assessment of building height and ground space. However, despite significant positive — respectively negative — correlation between density evaluation and building height — respectively ground space — perception, we did not discover any significant impact of visual immersion on density. We proposed several hypotheses to explain this unexpected results. In addition, a vast majority of the results obtained here can be useful both for 3D urban visualization and evaluation of user experience and navigation in virtual reality.

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