Looking At or Looking Out: Exploring Monocular Cues to Cre ate a See-Through Experience with a Virtual Window

Wijnand IJsselsteijn, Willem Oosting, Ingrid Vogels, Yvonne de Kort, Evert van Loenen

[w.a.ijsselsteijn@t ue.nl; w.oosting@tue.nl; ingrid.m.vogels@philips.com; y.a.w.d.kort@tue.nl; evert.van.loenen@philips.com]

Abstract

In indoor environments, having a view from a window plays an important role in human physical and psychological well-being – particularly if the view contains natural elements. In places where physical windows are absent or the view is highly artifact-dominated, virtual windows can potentially play a beneficial role. The current paper presents a research experiment on the efficacy of three monocular depth cues, i.e., motion parallax, blur, and occlusion, in engendering a window-like 'see-through experience' using projected photorealistic scenes. Results indicate that all three cues have a significant main effect on the viewer's 'see-through experience', with motion parallax yielding the greatest effect size. These results provide a first step in identifying and testing the perceptual elements that are essential in creating a convincing virtual window.

Keywords **Virtual windows, restorative environments, depth perception, motion parallax, view replacements**.

1. Introduction

The ubiquity of windows in places designed for human occupancy suggests that people attach special importance to the collection of functions that windows may serve in their environment. Indeed, several studies have shown the importance of windows on people's psychological and physical well-being. For example, Finnegan and Solomon [1] report that employees in work environments without windows report higher levels of work-related stress and lower levels of job satisfaction than those with access to windows.

Of all window functions (e.g., view to the outside, light source, knowledge of weather and time of day, regulating air quality, providing situational and orientation cues, etc.), the view out appears among the most significant [2]. In cases where windows are available, the content of the view outside is of particular importance. Several studies have reported on beneficial and restorative[8] effects of views onto a natural scene [3,4], whereas views onto human-built environments yield effects which are similar to having no window at all [5]. For example, Ulrich [7], in one of the classic studies in this area, reports on an experiment where patients recovering from gallbladder surgery where either assigned to rooms overlooking a natural setting or facing a brick wall. The ones with the view to nature had shorter post-operative stays, received less negative evaluation from nurses, and took fewer narcotic analgesics after surgery, than matched patients in rooms facing a brick wall.

Heerwagen and Orians [8] investigated how people compensate for the lack of windows in their office. They found that people without access to a real window view tended to use more visual materials (e.g., posters) than those with access to a window (even when compensating for the potential effect of extra wall space available through the absence of a window), and that the content of such materials was more likely to contain natural scenes and landscapes than urban scenes. For a detailed review of studies on the effects of windows on work and well-being, we refer to [9].

In addition to office environments, a number of specialised environments exist in which access to a window view is limited or entirely absent. For instance, in prison, many cells do not have a window view for control or safety reasons. In a number of hospital settings, such as intensive care units, patients only have a very limited view outside, if at all. And in spite of Jules Verne's visionary descriptions of the *Nautilus* providing an all-around view to its crew through several large bi-convex glass windows, submarines are in fact quite claustrophobic places where the only direct view outside is provided through a small periscope, and people have to live and work in such a confined space for long periods of time. What is noteworthy here is that these particular environments are almost inherently stressful to their inhabitants, for a variety of reasons, implying that a stress-reducing and restorative effect of a window view onto nature could potentially be quite significant, even if such a view is provided artificially.

As the majority of the world's population lives and

[8] The preference of people to have views onto a natural scene has been explained from an evolutionary perspective, in terms of potential access to resources such as food and safety [3]. Others have argued for the role that natural scenes may play in the restoration of depleted attentional resources [6].

works in increasingly urbanised environments looking out of their windows (if they have that luxury) onto concrete buildings, parking lots and roads, there is a solid basis for investigating whether artificial views from virtual windows could provide beneficial effects similar to those of real views. However, before such comparisons can be realistically made, we need to identify and test the perceptual elements that constitute a 'window experience'.

1.1. Creating virtual windows

Perhaps the earliest examples of pretend views from nonexistent windows can be found in antiquity. Trompe l'oeil paintings, dating as far back as 400 BC, were meticulously detailed paintings created to look entirely realistic in texture and dimensionality when observed from a particular vantage point.

Figure 6 A modern trompe l'oeil [10]

More recently, a number of commercial efforts are being developed aimed at (re)placing a window view. One example, the TESS Round Skylight, is shown in Figure 2. Semi-transparent photographs are placed in front of a light source to simulate a window in windowless medical

facilities.

Figure 2 TESS Round Skylight [11]

Such a virtual view to the sky and trees is expected to have a relaxing effect on patients as they undergo treatment. In line with findings of Ulrich [7], TESS has specifically targeted its virtual window application towards windowless

healthcare environments, such as critical care units and MRI environments (see Figure 3).

Figure 3 Virtual window at an intensive care unit [11]

Other innovative ways to bring the benefits of nature views into health care settings include the electronic window of nature that simulates the passage of daylight from dawn to dusk, created by Joey Fischer/Art Research Institute Limited and used first in the United States at Stanford [12]. SensoryScapes Panels even provide multisensory stimulation, combining nature views, soothing sounds and botanical aromas. They are specifically targeted towards windowless healthcare and interior office environments (see Figure 4).

Figure 4 SensoryScape panel at an office environment [13]

Figure 5 Armas Magic Window [14]

Figure 6 – Magic Window MW1000 [15]

Figure 7 Philips DreamScreen prototype at the Philips HomeLab [16]

The examples discussed thus far typically rely on transparent photo sheets with a light source placed behind them. Replacing content in these cases requires additional effort, and printing new photographic sheets can also be time-consuming and costly. In contrast, other manufacturers utilize electronic displays for the purpose of simulating window-views in a more flexible manner. For example, the Armas Magic Window systems, as presented in Figures 5 and 6, are linking an array of eight TFT-screens per window, enabling the user to change the content of each window view dynamically using a computer. Note how the physical separation between the different TFT screens is resolved by implementing a window frame.

The current project was carried out in the context of the larger Dreamscreen project of Philips Research, which has the aim to study how wall- and window-sized video displays in combination with directional audio cues and other sensory stimulation may create a convincing and beneficial immersive experience to users in their homes. The DreamScreen prototype presented in Figure 7 is based on five front-projected displays.

When comparing real space to virtual space, limiting ourselves to visual media for the time being, we find that real world perception has several critical features [17], which we will briefly discuss here in the context of creating virtual windows.

a) Static depth information is provided via several independent mechanisms (e.g., linear perspective, occlusion, texture density gradients, binocular disparity) that are consistent with each other and the observer's viewpoint.

Although none of the examples provided earlier employ binocular disparity as a cue, most other static depth cues are consistent in relation to each other, which is of course more challenging in the case of trompe l'oeil paintings than in cases where photographic projections are being employed. Most current window substitutes, however, do not take into account that the frame surrounding the window is perceived at a different depth layer than the view from the window. Assuming one is attending to the view outside, the frame will be disappearing in increasing optical blur as a consequence of the accommodation of the eye. Although adaptive blur generation based on gaze tracking would be the ideal solution, there are other, more practical options. One has been explored some years ago by CRL, a company that produced the Vistral screen surround which was placed over the screen edge like a picture frame. It generated a Moiré effect from two layered patterns of dots on either side of a glass plate and was extremely difficult to focus the eyes on. This tricked the accommodative system to signal that the Vistral screen surround and the screen itself belonged to different depth layers. As a consequence, it made the image on the screen appear to float in depth.

b) The resolution and intensity of the image is only limited by the sensitivities of our visual system.

In the case of backlit photographic sheets, the resolution is high enough for our visual system not to detect the grain. For electronic displays, the resolution will be lower, but may be compensated by the fact that one view is composed of a combination of multiple displays, as well as the likelihood that these images will be viewed from distances of more than half a meter or so, which substantially increases the resolution per visual angle. However, low brightness levels can still be a serious showstopper for electronic windows at this point in time, although arrays of ultra-bright LEDs show promise in this respect.

c) The effective image size fills our entire field of view, limited only by our facial structures, but without an externally imposed frame.

This is true in general when perceiving the world around us, with the interesting exception of windows, where we have learned to perceive a framed view as part of reality, and not as a mediated representation. The effect of different types of framing on the virtual window experience is a matter of empirical research. Some guidelines are available from prior work in office settings where shape and size of windows were manipulated using apertures [18]. Windows occupying less than 10% of the window wall were regarded as extremely unsatisfactory, whereas window sizes of 20% and larger were deemed most satisfactory. In addition, participants preferred a wide lateral scan, selecting wider windows over taller ones.

d) Dynamic depth information (i.e., motion parallax) is coupled to observer movement.

None of the examples of virtual windows discussed earlier presently support motion parallax, that is, a change in the relative position of objects as a result of observer movement in front of the display. Markus [19] argued that two-dimensional 'artificial windows' (screens that presented nature scenes) are ultimately unsatisfactory as a view replacement because of a lack of dynamic depth cues. He states: "Another criterion for successful window design might be a dynamic one – i.e., the amount of change in the view that takes place for a given change in the viewing position of the observer. As a result of this movement parallax, not only do objects at a different distance within the view change their relative position, but also the window-view relationship changes. This is why two-dimensional artificial windows, even when very carefully contrived, are unrealistic and soon cease to satisfy; they lack the 'depth' within the view and the parallax of window aperture-view is also absent."

Of course, in the area of interactive computer graphics known as virtual reality, head-tracked or head-coupled displays have been in use since they were introduced in the 1960s by Ivan Sutherland, providing the user with the movement parallax cue. Later, head-tracked desktop systems [20], sometimes also referred to as fish-tank virtual reality [21], provided the user with a window-like view onto a computer-generated, virtual world. However, only when combining the elements of photorealism with appropriate viewpoint-dependent transformations of the displayed scene can a window-like 'see through' experience become convincing. However, with the limits in current tracking and rendering speeds, real-time interactivity still trades off against photorealism, making a fully interactive photorealistic views difficult to attain at present, particularly when the content presented on the window is captured 'live'.

1.2. Rationale of the current study

The aim of the current study was threefold. First, we wanted to investigate if we could create a convincing see-through experience using a simplified approach to generating motion parallax in relation to a photorealistic scene, that is, only transforming the relationship between the window frame and the outside view, based on head movements, without transforming the relation between objects contained within the view. Secondly, we wanted to investigate the potential effects of window framing, as the addition of a frame is expected to provide additional depth information regarding the position (depth layer) of the frame vis-a-vis the outside view, via the occlusion or interposition cue, particularly in the case where motion parallax is present. Thirdly, we wanted to investigate whether the addition of blur to the boundaries of the frame would add to the 'see-through experience' as it would signal to the visual system that the frame was located at a different depth layer than the view being displayed.

Recent work most similar in spirit to our own is that of Radikovic et al. [22], who created a window substitute using a tracked wall-mounted display. Using a repeated measures design, they had 14 students assess this interactive virtual window showing a nature scene against a static picture of that same scene. They found that the virtual window supporting motion parallax was considered superior as a window substitute, also having a stronger effect on well-being (positive mood) than the static picture.

Although the Radikovic study usefully demonstrated the added value of motion parallax in simulating a view from a virtual window, in line with Markus' [19] prediction, their experimental manipulation of a head-tracked versus a static image was quite a basic one. We wanted to investigate whether in addition to motion parallax, other monocular depth cues could be usefully deployed in creating a window substitute, giving rise to a more convincing illusion that one is looking through a window at an outdoor scene, rather than at a flat image projected on the wall.

Figure 8 Schematic representation of the experimental 2x2x2 design: 8 conditions varying in blurring of the frame, the presence of an occluding cross-shaped frame, and the presence of motion parallax

2. Method

2.1 Design

The effects of the three types of monocular depth cues on the reported see-through experience were tested in an experiment with a 2 (Motion parallax: off vs. on) x 2 (Occlusion: off vs. on) x 2 (Blur: off vs. on) x 5 (Image) within subjects design. Five different images were used as viewing scenes (see Figure 9), the remaining manipulations are represented in Figure 8.

2.2. Participants

Twenty persons (12 male, 8 female) participated in the experiment, with ages ranging between 19 and 42. All participants had a (corrected) visus of at least 1 and had little or no experience with perception experiments. All were employees or thesis students at Philips.

2.3. Apparatus and setting

The experiment was conducted in a dedicated perception lab at the Philips High Tech Campus. A virtual window prototype was created using a BARCO Reality 6400 beamer, placed under a table draped with black cloth to make the beamer less apparent. The images were projected 1,70 meters wide and 1,28 meters high on a 12m2 plane white wall at a resolution of 1280x960 pixels and 24bits colours. The virtual window thus covered 18% of the wall size, approximately in line with Keighley's [18] recommendations regarding preferred window size. Furthermore a chair was placed behind the table at 5 meters distance from the projected window, resulting in a horizontal viewing angle of 19.3° and a vertical angle of 14.6° and providing participants a desktop to work on.

A Polhemus PATRIOT system was deployed to keep track of the participant's head location. A fixed magnetic field generator in combination with a magnetic field receiver attached to a headphone determined the six degrees of freedom. The system had a refresh rate of approximately 120

Hz and a tracking latency of around 0.7 milliseconds. The end-to-end system latency was approximately 15 milliseconds. Pilot tests showed that when participants did not make highly accelerated head movements, motion parallax could be simulated without too much delay. The range of the transmitter/receiver was about 0.75 meters forcing the participants to remain seated during the experiment.

Custom software was engineered to interface the information supplied by the head tracker over the RST232 port of a PC. Another program was written to interpret the readings of the tracker and superimpose the occluding cross-frame. In a pilot experiment, the optimal gain factor (ratio between image-translation and head-translation) was determined at 0.58. When viewing the scenes, the lighting level in the laboratory was 40 lux (as measured on the desk) to ensure that the projected view would appear brighter than the laboratory and the black occluding cross would form a silhouette similar to that of a window frame.

2.4. Stimuli and monocular cue manipulations

Five different images were chosen, depicting a varied set of scenes and with varying distances at which interesting objects were displayed. The images are depicted in Figure 9.

Motion parallax was created by using digital photographs with a very high resolution, of which the virtual window only showed a small part. The picture was virtually placed at some distance behind the window frame, such that viewpoint-dependent transformations differed between the window frame and the outside view as a whole. Tracked head movements of the participant resulted in matched translations of the image (the picture being moved in the same direction as the head to display the correct view), thus simulating motion parallax.

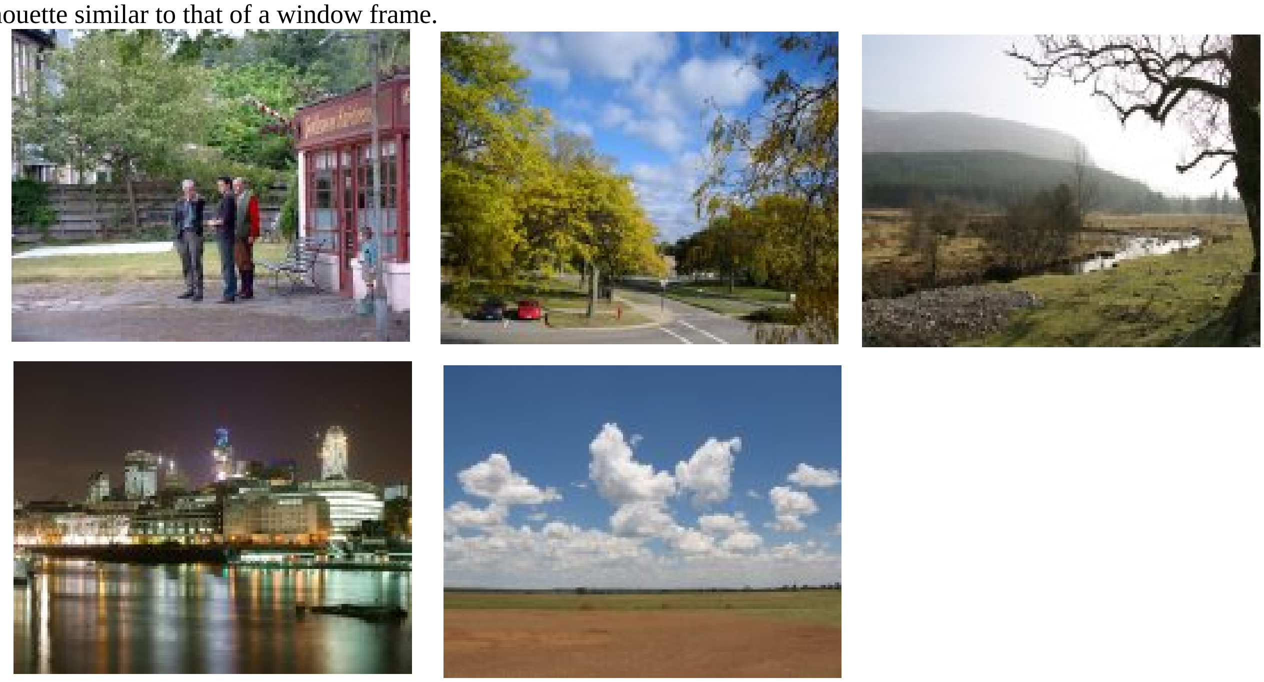

Figure 9 Five different images used as viewing scene: Hairdresser, First floor, Creek, Night Skyline, and Africa

Occlusion was implemented by superimposing a cross-shaped frame, as shown in Figure 10. The black bars of the cross were 5 centimeters wide, as measured on the wall.

Lastly, blur was manipulated by introducing a transparency gradient ranging from 0 to 1 over a distance of 1 centimeter starting at the edges of the frame and the edges of the cross.

Figure 10 Visible scene, without and with occluding frame

2.5. Measurement

Participants were asked to rate their 'see-through experience', which was defined as 'the feeling that you are watching *through* a window, that is, the feeling that the view is beyond the "window" instead of a slide of a window-view on the wall'. They marked their assessment on the scoring form using the scale depicted in Figure 11. After the experiment the scores were measured with a ruler. The full length of the scale was given 5 points.

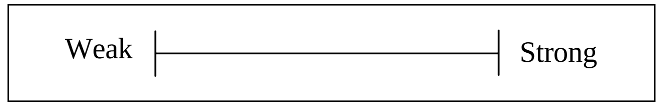

Figure 11 Scale used to assess 'See through experience'

2.6. Procedure

Upon entering the room, participants were seated behind the desk and received written instructions to make moderate lateral head movements when viewing a new scene and to watch "out" of the window, not directly at the frame.

Once the participants finished reading the instructions, they placed a headphone with the head-tracker on their head and the experiment leader dimmed the light. The program first presented a training session with examples of views with different monocular depth cues, to allow participants to get used to the setting as well as the task and calibrate their use of the scale based on the range of variance between the different views.

The experiment leader stayed in the room during the training session to answer possible questions and to check whether the participants interpreted the instructions correctly. Participants were encouraged to use the full scale during the actual experiment. Then the experiment leader left the room and the participant commenced with the experiment. The order of the images and views was counterbalanced between participants. During the loading time of each new view an inter-stimulus adaptation field (ISAF) was displayed to eliminate influence from a previous stimulus due to inheritance.

Participants were offered a small token of appreciation (a lollypop) for their time. The experiment lasted approximately 15 minutes.

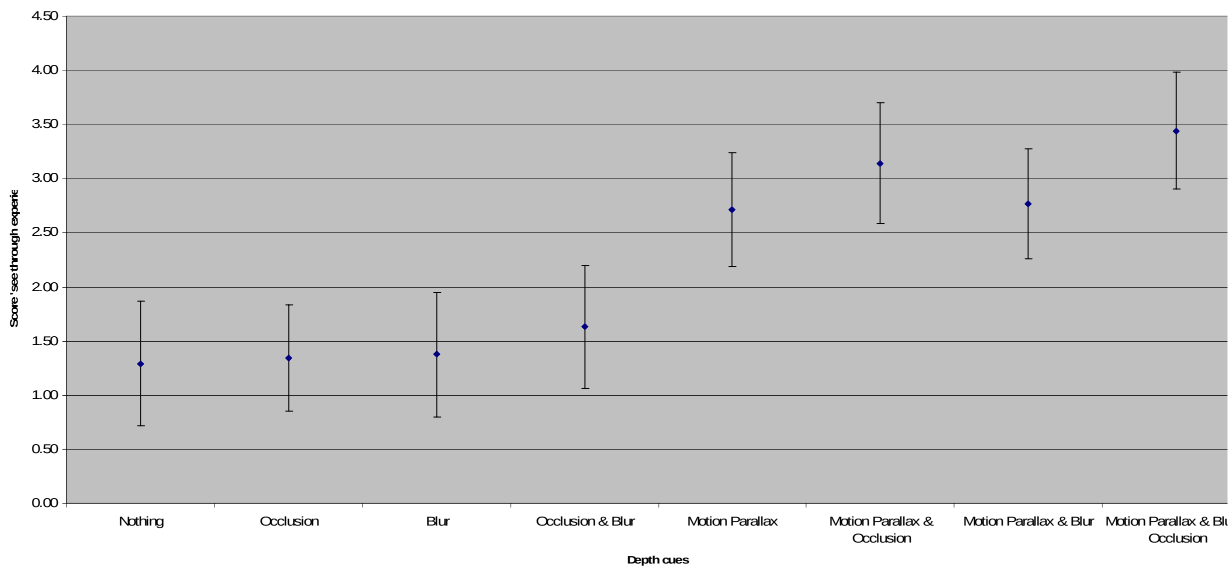

Figure 12 Mean scores and 95% confidence intervals for each of the 8 experimental conditions, averaged across participants and images.

3. Results

The effects of the three types of monocular cues on the reported see-through experience were tested in an experiment with a 2 (Motion parallax) x 2 (Occlusion) x 2 (Blur) x 5 (Image) within subjects design. The average scores for the five images in each of the experimental conditions are reported in Figure 12.

All three monocular cues show positive effects on the see-through experience. These results were tested in a Repeated Measures ANOVA, according to the full model. Motion Parallax showed a significant main effect ($F(1,19)=24.86$, $P<.001$). The experience without motion parallax was rated lower ($M=1.4$) than the experience with motion parallax ($M=3.0$). Although somewhat smaller, the main effect of Occlusion was also significant ($F(1,19)=8.70$, $p=.01$) .Viewing conditions with an occluding frame ($M=2.4$)

were rated higher than those without (M=2.0). The third main effect, of Blurred edges, also reached significance (F(1,19)=6.17, p=.02). Blurring the edges raised the see-through experience from M=2.1 to M=2.3. The last main effect, of Image, did not reach significance.

In addition, the interaction effect between Motion Parallax and Occlusion was significant (F(1,19)=4.71, p=.04), as well as the 3-way interaction between these two variables and Image (F(4,76)=3.68, p=.01. Further analyses showed that the effect of Motion parallax was enhanced for windows with an occluding frame compared to motion parallax without occluding frame for the 'hairdresser' image, but not for the remaining images.

Finally, the interaction between Occlusion and Blur almost reached significance (F(1,19)=3.88, p=.06), and the 3-way interaction Occlusion x Blur x Image was significant (F4,76)=2.49, p=.05. Occlusion was very effective for the 'hairdresser' and 'first floor' scene, less effective for the 'creek' and 'Africa' scene, and only effective in the 'night sky' scene when edges were blurred. No remaining effects proved significant.

4. Discussion

Taking the beneficial effects of windows as a point of departure, this paper presents an investigation on the contribution of three monocular depth cues, i.e., motion parallax, occlusion and blur, to the illusion that a wall-projected scene affords a window-like 'see-through experience'. These cues were selected on the basis of an analysis of the role they are thought to play in the perception of scenes through a window. Additionally, the three cues chosen were computationally inexpensive, which allowed their implementation in a virtual window showing photorealistic images.

A controlled experiment was performed, manipulating the three monocular cues in a 2x2x2 within-subjects design. The results indicate that all three manipulations had a significant main effect on the 'see-through experience'. The largest effect was produced by the motion parallax manipulation, in line with our own expectations as well as prior work [22]. Interestingly, the motion parallax effect was highly significant even though the implementation of motion parallax we used was a simplified one, only transforming the relationship between the window frame and the outside view, without transforming the relation between objects contained within the view. This is a promising result, as such a basic motion parallax simulation can be rendered in near to real-time, allowing people to look from their virtual window at any photorealistic scene, be they a static picture or a moving image. It is easy to conceive how such a window could provide a real-time view onto beautiful or exotic natural scenery through connections with various HDTV cameras placed around the world, much like the current widespread use of webcams that capture various kinds of environments, from homes, street corners, and offices, to the Eiffel tower or the African savannah. More realistic motion parallax rendering, such as those based on image-based rendering (IBR), as used by Radikovic et al. [22], are computationally more demanding and do not yet afford the near real-time rendering of such 'live' photorealistic imagery. It is an empirical question how our approach compares to IBR in terms of perceptual effect. Our prediction would be that for scenic views without foreground objects to speak of (e.g., views of mountains, deserts, sea, etc.), the simplified motion parallax approach will yield results similar to those that require more computational complexity. However, when foreground objects are salient, the simplified approach we used may provide cues that the surface one is looking at is, in fact, a flat 2D projection.

Although the effects of blur and the occluding frame were both much smaller in terms of effect size than motion parallax, their independent effects were significant nevertheless. This indicates that the 'see-through experience' we used as an indicator for how 'window-like' the simulation appeared, was indeed influenced by these monocular cues, in line with our expectations. Although none of the virtual window simulations we came across in our research apply selective blurring of the window frame as a depth cue, it appears that this cue yields a moderate effect on the realism of the simulated window, in particular signaling that the frame belongs to a different depth layer than the depicted view. However, we had not anticipated a strong effect of blur, as accommodation is known to be a fairly ineffective source of information for accurate depth discrimination [e.g., 23].

The superimposition of a cross-shaped frame across the entire view yielded a slightly larger effect than blur, but was particularly effective in conditions where motion parallax was present as well. The three-way interaction between Motion Parallax, Occlusion and Image was caused in particular by the 'hairdresser' image. This is quite understandable as the occluding frame partially obstructs the view onto the objects of interest in this image, being the people in front of the barber's shop. Thus, without motion parallax, that is, the ability to look *around* the occluding frame, the view would be irritatingly blocked. More generally, the combination of motion parallax and the superimposed frame gave people a convincing illusion that a stable foreground reference frame was available through which a continuous environment in the background (the scene) could be viewed. This result suggests that providing additional framing in head-tracked virtual windows may enhance the illusion of a continuous environment in the background that is distinct from the wall of the room one is located in. This interpretation is in line with other work on foreground occlusion, in particular that of Mergner and Becker [24] in relation to vection (illusion of self-motion) and Prothero et al. [25] in relation to presence. Thus, in the motion parallax conditions, a stable foreground frame facilitates the perception that the background scene is independent of the window through which it is perceived and continuous beyond the boundaries of the frame. Additional framing then provides more evidence for the stability of the window frame in relation to the outside view.

Based on the results reported in this paper, one area of future research we would like to pursue is the application of virtual windows to settings where access to windows is problematic, as discussed earlier. We have already seen a number of commercial efforts in the healthcare domain. However, such companies typically provide little if any data relating to the clinical effectiveness of their 'healing windows', and usually base their claims on studies of the effects of real window views. It needs to be investigated whether virtual windows will have similar beneficial effects as real windows, and which aspects of the 'window experience' most crucially determine such effects (see also [26, 27]). Based on our results, motion parallax will likely be an important factor, but other factors we did not consider, such as lighting levels, may prove to be equally important.

In addition to applications in health-related environments, virtual windows have great potential for leisure and entertainment, for example as an advanced home theatre system or as an enjoyable view replacement which shows, to quote Basil Fawlty, "herds of wildebeests sweeping majestically across the plains" from a Torquay hotel window. Virtual windows can offer relaxing effects in stress-prone underground environments, such as subways or underground parking lots. For example, the IN-Visible system [28] shows subway travelers a projected view of the exterior urban environment at ground level that one is traveling underneath. Such a virtual subway window can enhance feelings of orientation, but can also make underground traveling much more enjoyable.

The study of artificial windows constitutes a useful case study for presence research, where fundamental and applied issues are intimately linked together. Though clearly delimited, the 'window experience' is quite rich and inherently multimodal. Although the research reported here has only touched upon the investigation of three particular visual cues relevant to window simulations, many other sources of sensory information are of relevance in creating a convincing window substitute, such as stereoscopic imaging, spatial audio characteristics, temperature, light, air quality and flow, and olfactory cues, to name but a few. What is particularly interesting about virtual windows, however, is that they are one of the few simulations where the people confronted with the simulation need not necessarily know in advance that they are looking at a mediated environment. One important characteristic, discussed in this paper, is that windows are generally bounded by a frame, turning one of the intrinsic limitations of most display systems into an advantage. When future virtual windows will use unobtrusive head tracking and will update their high-resolution photorealistic view accordingly in real-time, the next generation of trompe l'oeil artifices will have arrived, fooling both the eye and the mind of unsuspecting viewers looking out.

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