The Role of Specular Reflection in the Perception of Transparent Surfaces – The Influence on User Safety

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Abstract. The perception of transparency in human's build environment constitutes a significant cognitive challenge, also affecting the user's safety. It is supposed that, apart from the mid-level vision transparency cues, specular reflection is also a key feature of the perceived image taken into consideration by the visual system. In the paper, this optical phenomenon was observed and estimated based on the author's own method, here called the "pictorial image analysis", which uses pairs of photographs: unmodified – showing the virtual image on the building's transparent façade, and modified – devoid of this image. The images were digitally processed to extract the reflection laid over the undisturbed transmitted image. The results show that evident specular reflection significantly improves the perception of transparent surfaces, but, in the case of excess or back-lit panes, it can hardly be used as perceptual cue.

Keywords: transparency perception, mirror-like reflections, building's façade.

1 Introduction

Large scale light-transmitting surfaces have been present in human's build environment since the advent of 19th and 20th century industrialized manufacturing methods. Smooth, faultless and frameless sheets of glass are difficult to perceive, especially on a diverse background, because of the high degree of transparency. As a result, perceptual mistakes occur, resulting in people accidentally walking into the transparent pane. Application of safety standard limits the number of instances of human-pane collision, but this "considerable threat to human safety" [1, p. 74] needs to be addressed. Measures should be taken to limit or avoid potential accidents and to understand the phenomenon better.

2 The Cognitive Mechanisms of Transparency Perception

At the mid-level vision stage – while creating the 3-dimensional model of the environment – the visual system recognizes transparency as a "special case of superposition" of surfaces [2, p. 257]. One of the key mechanisms depending on the pane's

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absorbance is detecting the difference in transmitted image luminance between the obscured and unobscured portion (called a *reference area*) of the field of view. If the entire field of view is occupied by the pane, no edge is visible (the *reference area* is missing) and this basic mechanism simply ceases to work. In such circumstances, the perception system must rely on other cues for the recognition of transparency.

High-level cognitive processes involved in the perception of transparency are supposed to be based on cues produced by the so-called *optical surface phenomena*. These include: *(i)* specular reflection – generated by glossy transparent materials, thus creating a virtual image, *(ii)* transmitted image distortion, *(iii)* light ray refraction, among others. It is supposed that perception of specular reflection is – apart from the mid-level transparency cues – a key feature of the perceived image that is taken into consideration by the human visual system in the perception of transparency.

3 Specular Reflections and Virtual Images

Specular reflection is formed on the surface of all materials (not only light-transmitting) that have a sufficiently well finished surfaces (the imperfections of the material's surface are smaller than the wavelength of light). In such conditions, uni-directional light reflection occurs and a virtual image is created. Specular reflection could be created on a flat mirror, resulting in an undistorted virtual image (apart from left-right inversion) or on a free-form, ovoid object. The latter case results in a heavily distorted virtual image taking the form of luminance *highlight* – an area of higher luminance, distinctly different than the observed object. The location of those highlights was proven to be an important cue for the visual system in decoding the ovoid shape of an observed object, as shown by Blake & Bulthoff [3, p. 240].

In the case of a transparent material, two phenomena occur simultaneously. Every smooth pane that lets light through without deflection, simultaneously reflects light uni-directionally and provides the conditions for the formation of a virtual image.

An undistorted virtual image of the environment is created upon the flat mirror surface. It conforms to the laws of perspective and is usually perceived as appearing "behind" the mirror, or "inside the object". This is due to an optical illusion (humans perceive light rays as radiating along straight lines).

The image generated by a flat mirror, does not differ from the real image (both cannot be distinguished in the retinal image). The lack of differences causes the virtual image to be further processed by the visual system in the same way as the real image. The formation of a virtual image on the pane of light-transmitting material results in an interesting optical phenomenon – the superposition of two images: a real one transmitted through a pane, and a virtual one formed by the reflected rays. Presumably, the perception system uses this property to identify optical transparency and pane orientation in a 3-dimensional space surrounding the observer [4].

4 Research Tools and Methodology

The presented analysis is based on photographs depicting large-scale panes of light-transmitting material where two overlapping images are perceived in specific case studies. Both the buildings' glazing and the free-standing panes of transparent materials were included in this stage of the research.

The core study was conducted through observation with its results recorded using digital equipment. It was assumed that the image recorded by the digital camera matrix reproduces the instantaneous image perceived by the observer with sufficient accuracy. The main analytical method applied in the paper is called "pictorial image analysis" and is based on a comparison of two photographs: *(i)* unmodified, showing the virtual image on the surface of a transparent material and *(ii)* modified – with the virtual image blocked by the polarizing filter (details below).

4.1 Data Acquisition

The buildings selected for the study were: the Thespian Housing and Office Building (by Mackow Pracownia Projektowa, 2012) and the Silver Forum Office Estate (by Archicom, 2007), both prominent examples of contemporary architecture, recognized worldwide. The Thespian was a nominee for the European Union Prize for Contemporary Architecture – the Mies van der Rohe Award. Twofold images of selected buildings were recorded using a Sony Alfa 100 reflex camera (10 Mpix), 10-20 mm Sigma lens and a polarizing filter. Out of 140 photographs shot on site, 4 most representative series were selected for further digital processing.

4.2 Image Post-processing and Tools of Digital Analysis

The analysis was carried out using the ImageJ post-production software [5] originally developed by the Research Service branch of the U.S. National Institutes of Health for analyzing medical image data. The software offered tools unavailable in other applications, like image calculations (image subtraction and difference) and exact pixel count (using histogram measurement). Image processing occurred in stages, including: *(i)* cropping the selected areas of corresponding recorded images, *(ii)* subtracting or differentiating the images in order to isolate the virtual image, *(iii)* thresholding the image to isolate the areas of the virtual image, and visualize them by color coding, *(vi)* measuring the percentage of façade pixels affected by the virtual image using the histogram function. The individual steps of image processing have been shown in Figure 1.

The individual character of the field study photographs (changing light and point of view conditions) prevented the use of standardized parameters for all processed series. The level of threshold had to be determined individually for every viewpoint in order to achieve optimal virtual image selection. It has to be stated here that in series 3 and 4, the subtraction operation (i.e. subtracting digital numeric value of one image from another image) did not achieve the desired result because of the high pixel values (reaching max. in grayscale) contained within the virtual image areas.

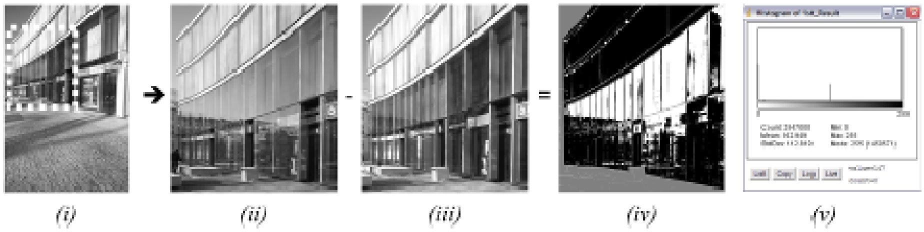

Fig. 1. Steps of image processing e.g. series 1: *(i)* image crop (dashed frame), *(ii), (iii)* image subtraction, *(iv)* image thresholding and color coding (black – façade area, white – virtual image), *(v)* measuring the percentage of façade pixels by using the histogram tool. Pictured building: the Thespian Housing and Office Building (by Mackow Pracownia Projektowa, 2012)

5 Pictorial Image Analysis and Results

In the "pictorial image analysis", a total of four series of images were analyzed. In two of them (series 1 and 2), the virtual image was isolated automatically, using the subtraction or differentiation tool of the ImageJ software and processed according to the above algorithm (see simplified graphical flowchart on Fig. 1). In the other two (series 3 and 4), the virtual image was isolated by tracing the outline based on the borders of the glazed portions of the façade. The results of the analysis are presented on the corresponding figures 2-5.

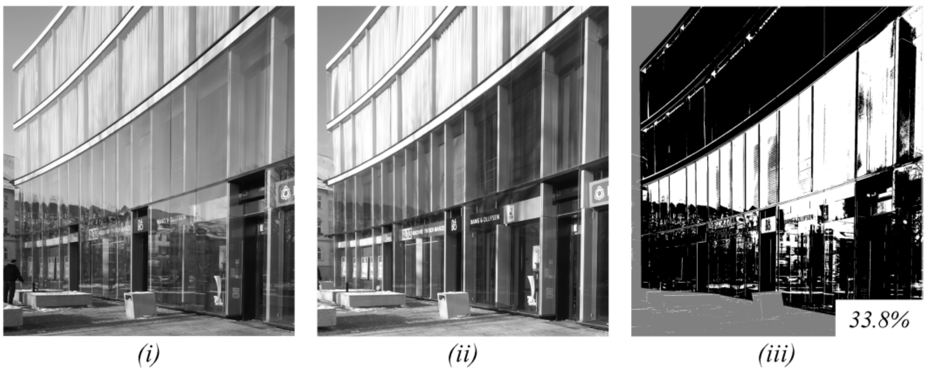

Fig. 2. Pictorial image analysis of series 1: *(i)* unmodified image, *(ii)* modified image with reflection filtered out, *(iii)* image thresholding and percentage calculation. Pictured building: the Thespian Housing and Office Building (by Mackow Pracownia Projektowa, 2012)

In series 1 (see Fig. 2), the virtual image of the surrounding buildings is visible in the lower part of the image, while the upper part of the virtual image is dominated by the reflection of the clear sky. The curvature of the façade makes the virtual image change gradually due to the different position and angle of the observed panes of glass. The glazed area obscured with the virtual image was calculated as 33.8%.

Fig. 3. Pictorial image analysis of series 2: *(i)* unmodified image, *(ii)* modified image with reflection filtered out, *(iii)* image thresholding and percentage calculation. Pictured building: the Thespian Housing and Office Building (by Mackow Pracownia Projektowa, 2012)

In series 2 (see Fig. 3), the virtual image is less prominent and vanishes as the angle of viewing increases (measured from normal). The image is dominated by trees, the reflection of the clear sky that was noticeable in the upper two stories do not affect transparency substantially. The glazed area overlaid with the virtual image amounted to 25.4%.

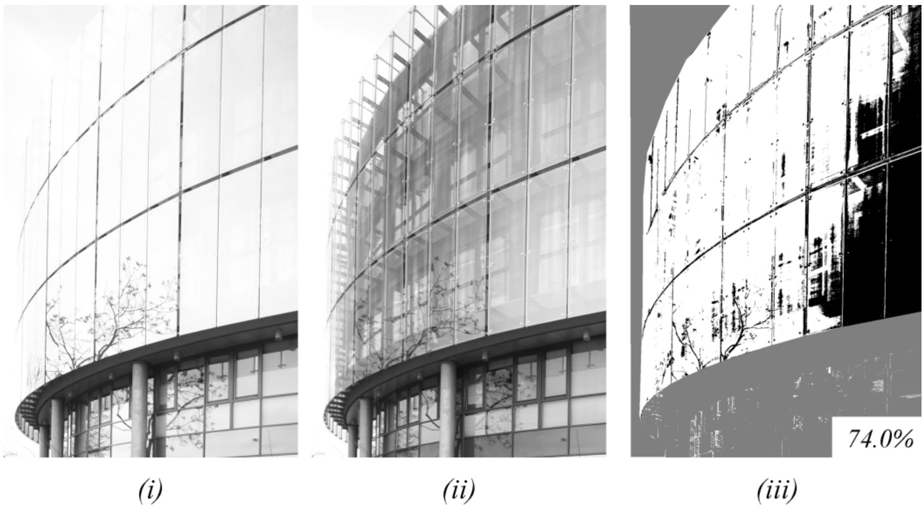

Fig. 4. Pictorial image analysis of series 3: *(i)* unmodified image, *(ii)* modified image with the reflection filtered out, *(iii)* image thresholding and percentage calculation. Pictured building: Silver Forum Office Estate (by Archicom, 2007)

In series 3 (see Fig. 4), the virtual image dominates the whole area of the transparent glazed façade. The substructure of the façade is not visible at all, it can be assumed that nearly the entire glazing is affected by the virtual image. Calculated values confirm this. The glazed area overlaid with the virtual image amounted to 74.0%.

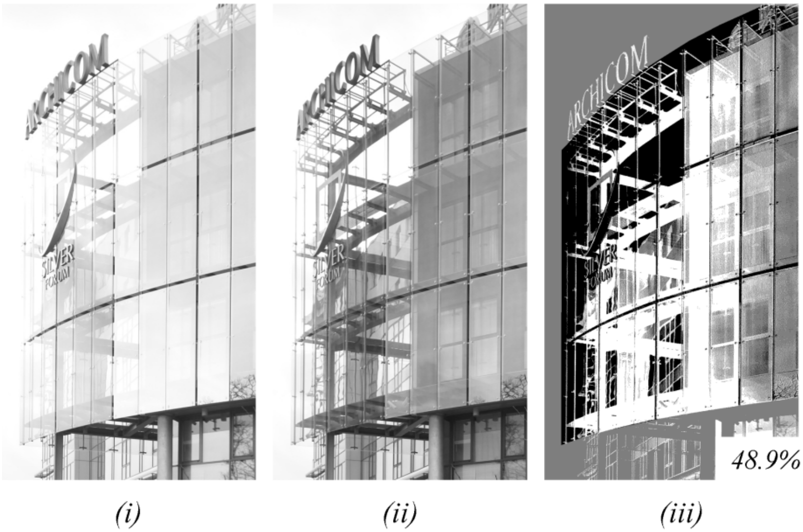

Fig. 5. Pictorial image analysis of series 4: *(i)* unmodified image, *(ii)* modified image with the reflection filtered out, *(iii)* image thresholding and percentage calculation. Pictured building: Silver Forum Office Estate (by Archicom, 2007)

In series 4 (see Fig. 5), a freestanding glazed screen is recorded projecting from the curved façade. The luminous flux balance makes this part of the glazing act differently in terms of optics. Since the panes are backlit, the virtual image is visibly weakened in this part of the façade, while the substructure and the background are visible. The glazed area overlaid with the virtual image amounted to 48.9%.

In all series, the application of a polarized filter in modified images lead to at least partial elimination of the virtual image. The area of glazing affected by the virtual image was calculated (white to black+white pixel ratio) was measured based on the histogram.

6 Discussion

In series 1 and 2 – when bright sunlight illuminated the photographed buildings – the share of the area overlaid with virtual image is smaller in proportion to the overall glazing area. In series 3, the larger share of the virtual image's covered area occurs due to the high luminance of the cloudy sky. Series 4 depicts both phenomena, since the glass panes are partially backlit. These differences in the visual outcome are caused by the difference in lighting conditions at the moment of image recording and allow to study the phenomena of how different lighting scenarios can influence the perception of transparency.

Based on analyzed images, the following possible cognitive mechanisms of transparency recognition based solely on reflection could be identified:

1. *image superposition* – a mechanism based on the local increase of luminance of the transmitted image resulting from the overlap with the virtual image (visible as moderate superposition in unmodified images in series 1 and 2 of 33.8% and 25.9% of area). The object (surface, other building, sky) that is reflected in a transparent pane always has a non-zero luminance. A virtual image resulting from this reflection overlaps with the real image transmitted through the pane. The reflected and transmitted luminous fluxes con-fuse (mix) and, if the luminance of the virtual image overpowers the luminance of the transmitted image, a local increase of luminance is perceived. If the luminance of the virtual image is lower than the luminance of the transmitted image, the visual outcome remains unaffected (no darkening occurs!).

Apart from the moderate superposition of the two images, two perceptual extremes could also be recognized, which lead to the obvious impairment in the perception of transparency:

2. *low luminance or total lack of the virtual image*. In the absence of a filtered out virtual image, the visual system has to rely solely on mid-level cues. In modified images, the most reliable cue – the reference area – is missing. Therefore, the perception of transparency in the modified images of series 1, 2 and 3 is much more doubtful than in series 4, where an evident reference area is present. In optical terms, the glazing projecting on a separate supporting structure works as a screen. Only a part of the background is veiled by the screen, hence obscured and un-obscured parts of the field of view could be compared by the visual system.

3. *excessive luminance of the virtual image*. Excessive luminance of the virtual image blocks the transmitted image totally. The transparent surface is indistinguishable from the mirror surface and its appearance depends on the geometry of the environment surrounding the observer and the luminance of the surface reflected in the pane (the cloudy sky in series 3 and 4 in 74.0%. and 48.9%).

Other issues should be researched in the future, according to the proportion of the virtual image visible on the pane: *simultaneous observation* of a distorted virtual image and an undistorted transmitted one, as well as the conditions of *variable eye accommodation* resulting from different real and apparent distances of the observed objects from the observer.

7 User Safety

Transparency perception is deeply linked with the recognition of invisible barriers, often in the form of a glazed pane. If this process fails, collision might occur. As previously shown in other papers by the author, increasing the human ability to ideally perceive transparent materials could be "fulfilled only by local suppression of transparency" [1, p. 80]. In this context, the above observed phenomena of *moderate image superposition* and *excessive luminance of virtual image* seem to be safe, as the obstruction of the real image by the virtual image sufficiently increases the ability to locate the pane correctly in a 3-dimensional environment surrounding the observer. The *lack of a virtual image* seems to be of real concern here, as this condition removes the mid-level cues by which the visual system can judge the transparent pane's location.

8 Conclusions

The conclusions based on the analysis of four series of images are as follows:

1 The presence of a virtual image significantly improves the perception of transparent surfaces. The absence of this important cue (e.g. in panes with special coatings) results in a decreased ability to recognize transparency and creates hazards for users.

2. In the case of high luminance values of the virtual image, the impression of virtual depth (virtual space, "world behind the mirror") is created. Attenuation of the transmitted image and amplification of the virtual one can lead to spatial disorientation, especially if the observers are to deal with multiple reflections.

3. The virtual image can hardly be used as a perceptual cue in the case of back-lit panes. This is due to the fact that the levels of illuminance on the opposite side of the pane are usually significantly higher than on the observer's side. This imbalance usually results in a visibly weakened virtual image that does not influence the image transmitted through the pane.

The elimination of the virtual image is supposed to impede the perception of transparency to the same extent as the excess of virtual image. The vital role of the virtual image in the process of recognition requires further study and research, possibly enriched with some field studies.

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