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DESIGN CRITERIA FOR USER-CENTRED SHADING SYSTEMS: A VR-BASED STUDY ON USER PREFERENCES

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Abstract

Solar shading systems are essential for creating comfortable indoor climates, reducing glare, and enhancing overall building energy performance. In addition, they influence how building users connect with their environment and shape architectural spatial experiences. However, conventional systems often fail to effectively address variable environmental conditions and individual user preferences. Advancements such as dynamically switchable glass and films, integrated with sensor technology, theoretically offer new possibilities for user-centred façade systems as these technologies enable real-time optimization of glare reduction and outward visibility by detecting user positions and viewing directions. Due to the novelty of these systems, their design requirements remain underdeveloped. A laboratory study using virtual reality technologies investigated user preferences for pixelated façade systems. The results indicate the importance of carefully balancing the expressive and functional behaviour of the system. Insights were gained for both static and dynamic façade configurations, providing a first foundation for future system design.

Keywords: Daylight, Façade Systems, Virtual Reality, User-centricity, User Preferences

1 Introduction

Sun protection systems play a critical role not only in preventing glare but also in fostering a comfortable indoor climate through seasonally optimized utilization of solar gains (Bui et al., 2020). Additionally, within the framework of integrated artificial and daylight control strategies, they can significantly enhance the energy performance of buildings (Mukherjee et al., 2010; Soori & Vishwas, 2013). Furthermore, as variable façade components, they hold psychological significance for building occupants. By functioning as interfaces between interior and exterior spaces, these systems influence our connection to the environment (Ko et al., 2020) and shape the architectural spatial experience through their various operational states (Cucuzzella et al., 2022).

Interestingly, conventional shading systems, despite their diverse functions, prove to be relatively limited in their application today. On the one hand, shading elements are typically designed to cover large areas in order to minimize mechanical components. On the other hand, they are usually mounted at the top edge of the window and extended downward when in use. These design constraints result in systems that, in specific functional scenarios (e.g., glare prevention), do not allow for consideration of differing user requirements. As a result, variable environmental conditions or individual user preferences cannot be effectively accommodated by conventional systems.

Accordingly, the possibility of mutual optimization of contradictory target criteria is not only relevant regarding the energy consumption of buildings (Hammes et al., 2024). As a fundamental interface between interior and exterior, the essential properties of windows are significantly influenced by shading systems, particularly when there is a prioritization of energy-related or glare-related objectives. For example, early studies have already demonstrated correlations between window views and postoperative patient recovery rates, psychological well-being, and pain perception (Ulrich, 1984). Furthermore, bright, daylight-filled hospital rooms have been shown to positively impact the average length of patient stays (Choi et al.,

2012). Better access to daylight and windows is also advocated in school design, particularly with the aim of counteracting the growing epidemic of myopia in children (Hobday, 2016). In addition, there is extensive evidence supporting the relationship between window views and occupants' comfort, satisfaction, and overall emotional well-being (Ne'Eman & Hopkinson, 1970; Ne'Eman, 1974; Boyce et al., 2003; Aries et al., 2010; Veitch et al., 2013; Jamrozik et al., 2019).

To enable a mutual optimization of different requirements, such as minimizing obstruction of the view outside while addressing existing glare issues, it would be necessary for systems to fulfil two fundamental properties. They should (1) shade only those areas of the window surface that are absolutely required to meet a specific need, thereby leaving the remaining areas available for optimizing other demands, and (2) function as real-time reactive systems that respond not only to changing external environmental conditions but also to interior conditions, such as adapting appropriately to changes in user positions. At least theoretically, such systems could already be addressed technologically today.

For example, dynamically switchable glass and films offer the potential to create user-centred systems through pixelated façade applications (Tong et al., 2021). These systems can theoretically take individual preferences into account while simultaneously optimizing glare reduction, energy efficiency, and outward visibility by enabling control of targeted subareas of window surfaces. In addition, computer vision functionalities allow the implementation of real-time reactive systems that can adapt to user positions (Hartmann et al., 2010) and gaze directions (Wang et al., 2021), thereby improving user comfort compared to current systems, which primarily rely on predefined assumptions.

However, due to the novelty of these technologies, they are still relatively far from being market ready. Moreover, dynamically switchable glass and films in particular are, due to their cost, hardly scalable to the size of entire building façades in a pixelated form. It is also problematic that fundamental design guidelines for their development are currently lacking, and their specific impact on the architectural spatial experience has not yet been quantified.

To address this challenge, a systematic laboratory study was conducted to investigate user preferences regarding the architectural appearance of pixelated façade systems in interior spaces, using virtual reality (VR) technologies. The study primarily focused on examining architecturally relevant design parameters and compared a pixelated façade system in various configurations to the characteristics of conventional shading systems. Both design-relevant conditions and the effects of extended user-centred scenarios were considered. We hypothesized that systems acting in a user-centred manner would generally receive more favourable subjective evaluations, but that their acceptance could fluctuate significantly depending on the observer's position due to the shift from conventional window surfaces to a more media-like façade. Furthermore, we assumed that the increased reactive behaviour of the shading system might lead to acceptance issues when pixel density becomes too high.

2 Methods

2.1 Study Population

The study included 36 participants (20 women, 16 men) with an age of $30,06 \pm 9,67$ years. Men ($30,25 \pm 11,49$) were slightly older than the women ($29,90 \pm 8,25$). Approximately half of the participants (47%) had previous experience with VR environments, with 8% being frequent users. Male participants were significantly more experienced in VR than females and most participants (55%) were using visual aids (e.g., contact lenses or glasses) at the time of study participation.

Before participating in the study, all participants were screened for colour vision deficiencies using Ishihara colour charts. Individuals who misidentified one or more charts, or who reported health issues potentially incompatible with the use of VR headsets (e.g., epilepsy), were excluded from participation. All participants provided written informed consent prior to the start of the study and received a financial compensation of €50.

2.2 Laboratory Setting and Virtual Environment

The study was conducted in a windowless room on the premises of Bartenbach GmbH in Aldrans, Austria, which was equipped with a VR system (Valve Index, Valve Corporation, USA). The entire study was conducted within the virtual environment, and all participants remained stationary during the testing phase.

The virtual test environment was based on a 3D model of the former research and development building of Bartenbach GmbH in Aldrans, Austria. The building includes, in addition to two individual offices and a meeting room, an open-plan office of approximately 160 m², accommodating a total of 28 workstations. The office building is characterized by a high proportion of natural daylight, achieved through a fully glazed southern façade and north-facing skylights. Using Radiance (Version 5.2, <http://www.radiance-online.org>), a mean daylight autonomy $DA_{500,8-18}$ of 81,56% was determined for the building based on the normative minimum illuminance of 500 lx according to EN 12464-1 (see also Hammes et al., 2022). To prevent glare and thermal overheating, the south façade features solar shading screens and external static daylight louver, which were specifically dimensioned and designed to optimize daylight performance for the building's geographical location (Fig. 1).



Figure 1 – Interior view of the R&D building with the glazed south façade and lowered solar shading screens (left), and exterior view of the building with the static daylight louvers (right).

The virtual representation of the building essentially included all core aspects of the architectural spatial geometry as well as the existing division of the south-facing window areas. However, in some respects, a simplified representation method was applied. On one hand, the static daylight louvers were not modelled in the virtual environment, as they conflicted with the requirements of the user-centred, pixelated façade system. Furthermore, the horizontal window divisions were omitted to maximize the continuous window area in the building. Although colour tones and key furnishings were transferred into the virtual model, they were both visually and photometrically stylized to simplify perception and avoid conflicts with the lack of photorealism.

Regarding the season and time of day in the virtual environment, no specific point in time was defined. The position of the sun was realistically assumed, implemented based on empirical values and kept static throughout the study. The primary aim of the daylight situation depicted was not to create a photometrically accurate spatial environment, but rather to generate an interpretable setting that would allow for an architecturally oriented evaluation. This also applied to the qualitative implementation of the shading elements in the scenarios under investigation, which were designed to be product- and material-neutral by modulating the alpha value of a light grey tone.

2.3 Shading Scenarios

2.3.1 Standard Scenario




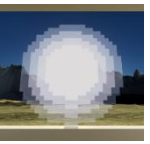
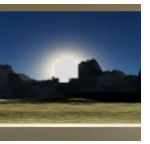
The standard scenario for shading was based on the existing situation in the R&D building. The solar shading elements covered the full width of each window area and were closed whenever the corresponding workstation in the virtual environment was occupied. The closure was implemented across the entire window surface, consistent with the existing system control.

2.3.2 User-centred Scenarios

The user-centred scenarios were based on a pixelation of the entire window area, where the shaded regions for each occupant were determined in real time. In the first step, a cone with its apex at the user's head position and its base defined by the outline of the virtual sun sphere was intersected with the window surface. The resulting intersection area was considered the minimal shading area required for each user to prevent direct glare from the sun. The actual shaded window areas were subsequently derived from both the calculated intersection area and the parameterization of the pixelated façade system.

The system could be adjusted according to three key parameters: (1) The pixel size, which defined the physical size of a pixel. All pixels were assumed to be square throughout the study. Every pixel fully or partially intersecting the calculated shading area was shaded 100%. Increasing the pixel size resulted in a lower resolution and a coarser pixelation of the shading area. (2) The shading offset, which was defined as an offset to the calculated intersection area, allowing the shaded region to be enlarged. (3) Finally, a fade-out could be applied to the extended shading area created with the shading offset. The fade levels were defined linearly based on the number of pixels touched by the fade area, meaning, for example, a 1-pixel fade zone would result in a pixel alpha value of 50% (100% in the core area, 50% in the fade area, 0% in the clear window area). Based on these three parameters, a total of six different preset scenarios were defined for the pixelated façade system (Tab. 1).

Table 1 – The six predefined shading scenarios used in the study, resulting from different parameterizations of the façade system.

Scenario	1	2	3	4	5	6
Pixel size	0,5	0,3	0,3	0,1	0,1	0,1
Shading offset	1,2	1,2	0,6	1,2	0,6	0,2
Fade-out	no	yes	yes	yes	yes	no
Example image						

The dimensions of the shading elements in the predefined scenarios ranged approximately from 10 cm (providing shading for the head of a building occupant) to 80 cm (shading the upper body and workstation of a building occupant). Since the shaded window areas were determined based on the user's head position, they responded to changes in the user's position in real time, provided that the newly calculated intersection area addressed new pixel regions or no longer covered existing ones. Changes in pixel transparency were smoothly transitioned over 200 ms to avoid abrupt switching of pixels and thereby prevent potentially disruptive effects. In cases where two or more user areas overlapped, the maximum required pixel alpha value was applied.

2.4 Outcome Measures

Several questionnaires were administered during the study to measure the perceived qualities between the shading scenarios. VR usability was rated using the System Usability Scale (SUS; Brooke, 1996) to capture the general experience associated with virtual reality. Each shading scenario was rated across eight dimensions using bipolar adjective pairs (supportive–obstructive, bright–dark, efficient–inefficient, pleasant–unpleasant, concentration-enhancing–distracting, good–bad, relaxing–exhausting, too much–too little) on a 10-point Likert scale.

All questionnaires were administered orally in German by the study supervisor, and participants' responses were recorded to avoid the need to remove the VR headset during the evaluation process. To ensure consistency, the exact wording of all questions was standardized for all participants prior to the start of the study.

2.5 Study Protocol

At the beginning of the study, participants were guided into the real-world setting of the open-plan office in the R&D building (Figure 1), where they could gain an impression of the actual architectural spatial qualities and material characteristics of both the building and furnishings, as well as the integrated shading system. During the observation period, all shading systems were closed regardless of the existing daylight conditions. Afterwards, participants were led to the experimental room, where they were instructed about the study procedure and trained in the use of the VR headset. Finally, they had 10 minutes to become familiar with the VR environment before the actual study began.

The study was conducted as a block-randomized repeated-measures design. A total of three blocks were carried out, each featuring different room usage scenarios and observer positions. In the first block, participants occupied the open-plan office alone, standing along the north façade and facing east, allowing an overview of the entire office. In the second block, five additional virtual persons were introduced: one moving along the central aisle and four seated at various workstations (Figure 2). In the third block, participants changed to a seated position at a central workstation, facing west along the south façade.



Figure 2 – Exemplary depiction of an evaluation situation from a standing observer position along the northern façade, with the presence of virtual building occupants.

Within each block, the six user-centred shading scenarios were presented in randomized order. In each situation, participants had 2 to 3 minutes to freely explore the space and observe the behaviour of the pixelated façade system. This was followed by a rating of the situation using the 8 subjective scales before the next scenario was shown. The standard scenario was rated once before and once after the completion of all three blocks. In both cases, participants rated from the standing, room-overviewing position in the presence of virtual room occupants (usage scenario of Block 2).

After completing the evaluations for all blocks, participants filled out the System Usability Scale (SUS) questionnaire and were debriefed by the study supervisor.

2.6 Statistical Analysis

For all statistical tests, the corresponding assumption checks regarding normality (Shapiro-Wilk test) and/or equality of variances (Levene's test) were conducted. If assumptions for data analysis were violated, non-parametric statistical tests were used as an alternative.

Descriptive statistics are presented as number of participants and percentages of total participants. Comparisons of two groups were conducted using paired-samples t-tests. For group comparisons (e.g., comparing the different shading scenarios), an analysis of variance (ANOVA) was applied. For significant effects, means and standard deviations as well as effect sizes (either Cohens d or partial eta-squared η^2) are reported. Figures show means and 95% confidence intervals of means. All analyses were performed at a significance level of 0,05 (two-tailed) using JASP (Version 0.18.3.0).

3 Results

3.1 Quality of the VR environment

The quality of the VR environment used in the study was rated as very high by most participants. 29 participants (80%) perceived the provided environment as realistic or very realistic, and 28 participants (78%) rated the quality of the device as high or very high. Furthermore, 34 participants (94%) reported that the VR environment allowed them to focus on the tasks without distractions during the study. This was also reflected in an overall System Usability Score (SUS) of $74,9 \pm 12,0$.

3.2 Pre-Post Assessment of the Standard Scenario

The conducted paired-samples t-tests revealed no significant differences in the dimensions supportive–obstructive, efficient–inefficient, and concentration-enhancing–distracting. However, significant differences emerged in the other assessed dimensions.

After experiencing the pixelated façade system, the standard scenario was perceived as significantly darker (Pre: $3,8 \pm 1,9$; Post: $4,7 \pm 1,5$; $p = .04$; $d = 0,235$), more unpleasant (Pre: $2,2 \pm 1,5$; Post: $4,5 \pm 2,3$; $p < .001$; $d = 0,244$), more exhausting (Pre: $2,9 \pm 1,6$; Post: $4,2 \pm 2,2$; $p = .004$; $d = 0,216$), and worse overall (Pre: $3,1 \pm 1,8$; Post: $4,7 \pm 2,1$; $p = .003$; $d = 0,268$). The scale too much–too little showed a trend toward difference (Pre: $4,9 \pm 1,3$; Post: $4,3 \pm 1,5$), though this was not statistically significant ($p = .08$).

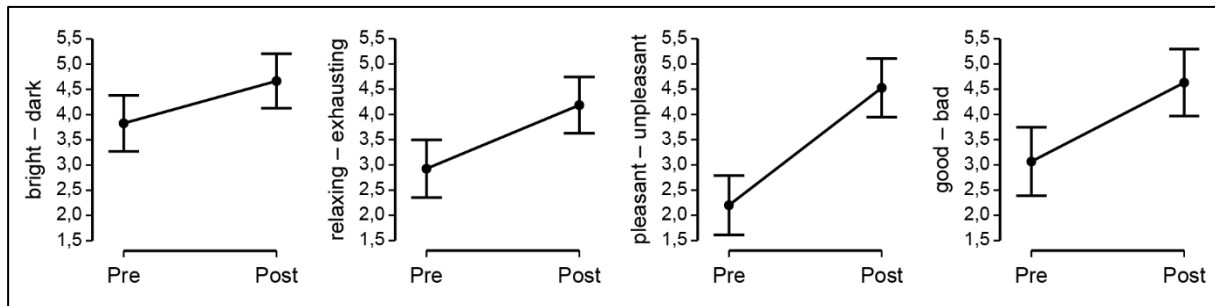


Figure 3 – Significant effects of the pre-post comparisons of the standard shading scenario.

3.3 Comparison of the different Shading Scenarios

The ANOVAs of the group comparisons between the individual shading scenarios showed significant differences in all areas (all $p < .01$; η^2 between 0,066 and 0,131), except for the dimension efficient–inefficient ($p = .147$).

The post-hoc tests conducted yielded varying results depending on the dimension assessed. For the dimensions concentration-enhancing–distracting, relaxing–exhausting, and good–bad, no systematic effects could be identified.

Partial systematic effects were observed in other areas. For example, scenarios 1 ($5,6 \pm 2,6$) and 4 ($5,1 \pm 2,6$) were perceived as significantly more obstructive compared to the other scenarios, but the ratings did not differ systematically from the others (almost all $p > .05$). A similar pattern emerged for the dimension pleasant–unpleasant, in which scenarios 1 ($5,8 \pm 2,3$) and 4 ($5,2 \pm 2,2$) were rated as noticeably more unpleasant. However, the effects were again not systematic (almost all $p > .05$).

Clear effects were found with regard to brightness. Scenario 6 was rated as the brightest scenario ($2,4 \pm 1,9$), whereas the standard scenario was rated as the darkest ($4,7 \pm 1,5$). Both scenarios differed significantly from the remaining scenarios (all $p < .05$), while the remaining scenarios did not differ from each other (all $p > .05$). At the same time, scenario 6 was rated as clearly too little in terms of the dimension too much–too little ($5,8 \pm 2,0$). This scenario differed significantly from all other scenarios (all $p < .05$), whereas the remaining scenarios did not differ from each other (all $p > .05$).

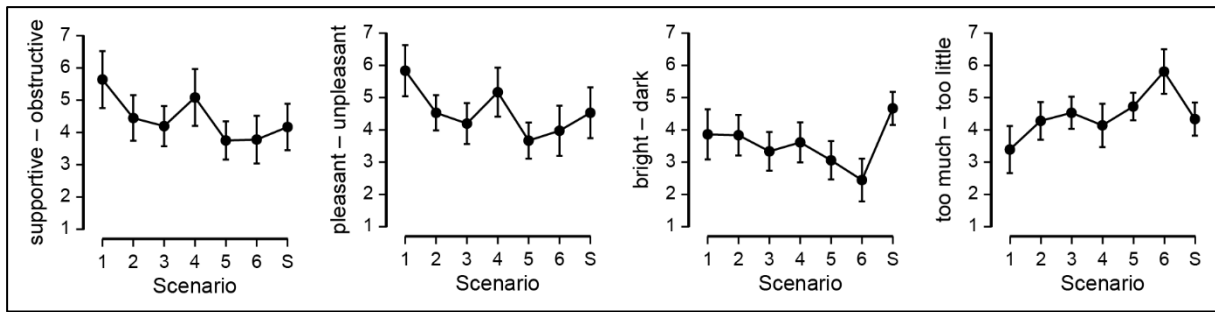


Figure 4 – Significant effects of the group comparisons of the different shading scenarios.

3.4 Impact of Room Occupancy and Observer Position

To evaluate the effects of the presence of virtual office users and the observer position on the assessment of user-centred shading scenarios, paired-sample t-tests were conducted. The results revealed a significant effect on the perceived brightness of the evaluated scenarios in both cases.

The scenarios were perceived as significantly brighter when no virtual office users were present (unoccupied: $2,7 \pm 1,6$; occupied: $3,4 \pm 1,0$; $p < .001$; $d = 0,070$). Additionally, the scenarios were perceived as significantly brighter from the standing observer position 1 compared to the window-side seated observer position 2 (P1: $3,4 \pm 1,0$; P2: $4,1 \pm 2,6$; $p < .001$; $d = 0,068$). No significant differences were found in any of the other evaluation dimensions (all $p > .05$).

4 Discussion

The results of this study provide first important insights into the perception and user preferences regarding user-centred shading systems. The chosen approach of evaluation within a virtual environment proved to be beneficial. The high usability score and the generally positive assessment of the VR environment support the suitability of virtual reality as a tool for design evaluation, particularly for assessing subjective impressions of spatial and atmospheric qualities in early conceptual phases. This is also supported by the existing literature (Johnson et al., 2019; Zou et al., 2023).

The comparison of the individual shading scenarios revealed significant differences in most evaluation dimensions, with the exception of perceived efficiency. While no fully systematic pattern emerged in some of the dimensions, scenarios 1 and 4 were generally perceived as more obstructive and unpleasant. However, the lack of consistent statistical significance in these areas suggests that user acceptance is likely influenced more by nuanced contextual or aesthetic factors than by a simple preference gradient. This becomes especially evident when considering the design characteristics of these scenarios, which were defined by extremely high or low pixel-to-offset ratios.

From a design perspective, this highlights the importance of carefully balancing the expressive and functional behaviour of the system. Pixelated patterns or densities, particularly in static or less personalized configurations, can appear overly intrusive or visually dominant, potentially undermining the user-centred intent of such systems. This calls for adaptable design strategies that allow for variations in opacity, rhythm, and movement based on environmental conditions and user preferences.

The findings therefore support the initial hypothesis that the transition from transparent window surfaces to a pixelated, media-like façade presents both opportunities and challenges for user acceptance.

One of the clearest and most meaningful findings relates to the perception of brightness. Scenario 6 was consistently rated as the brightest, while the standard scenario was perceived as the darkest. Notably, despite its bright appearance, Scenario 6 was also perceived as providing too little shading. This highlights the delicate balance designers must strike between

daylight provision and shading performance. This remains a central theme that is also frequently mentioned in other contexts in the existing literature (Tuaycharoen & Tregenza, 2007; Piccolo & Simone, 2009; Yun et al., 2011; Lee et al., 2022).

The study further illustrates that brightness is not evaluated in isolation, but in relation to subjective feelings of comfort and adequacy. As such, design strategies for adaptive façades should go beyond measurable lighting levels and take into account the perceptual impact of dynamic light modulation on users.

Another important and somewhat surprising finding of the study is that neither room occupancy nor observer position had a significant impact on the evaluation of the façade system (except in terms of perceived brightness). The assumption that spatial context, particularly the interplay between human presence and observer perspective, would strongly influence the perception of architectural qualities in façade systems was therefore not supported by the results. To the best of the authors' knowledge, there is still insufficient literature available in this area. In the future, it should be clarified whether this represents a systematic effect, which would mean that observers do not evaluate scenarios solely based on gaze-direction-related information but rather adopt a transcendental evaluative position.

Another key finding of the study emerged from the pre-post comparison of the standard scenario, which revealed a marked decline in its evaluation following exposure to the pixelated, dynamic façade concepts. After interacting with the user-centred designs, participants perceived the standard environment as significantly darker, more unpleasant, and more exhausting.

This shift suggests that dynamic, user-oriented shading systems can recalibrate occupants' expectations regarding spatial atmosphere and comfort. It highlights the potential of such systems not only to meet functional requirements but also to influence aesthetic and emotional responses to architectural spaces, which is also supported by the existing literature (Shemesh et al., 2017; Mfon, 2023; Wang et al., 2024).

4.1 Limitations

While the study provides meaningful insights, several limitations should be acknowledged. First, the shading scenarios examined relied solely on circular or rounded pixel patterns. It remains unclear how alternative geometries, such as linear, organic, or biophilic forms, might influence spatial perception and acceptance.

Furthermore, all evaluations were conducted within a single architectural setting. Since factors such as view quality and room typology heavily influence daylight preferences, the results cannot be generalized to other contexts without caution. Finally, although VR proved highly effective for this type of exploration, real-world validation is still necessary. Material qualities and light behaviour in physical environments may differ from virtual approximations and therefore affect user responses.

5 Conclusion

The results of this study highlight both the potential and the complexity of user-centred shading systems. While dynamic, responsive façades can positively influence user experience and recalibrate expectations, they must be carefully attuned to context, perspective, and perceptual thresholds. Pixelated façade systems in particular offer promising future potential by enabling enhanced optimization options. These make it possible not only to pursue sustainability-related goals more effectively, but also to adequately reflect user-centred objectives.

At the same time, however, these expanded capabilities also open up a broader set of challenges, as façade design options must be adapted not only to architectural concepts but also to individual user requirements in order to ensure long-term user acceptance. For architects and designers, the key takeaway is clear: successfully integrating adaptive shading requires more than technical precision. It demands a deep understanding of user perception and spatial atmosphere.

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