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Subjective and physiological responses towards daylit spaces with contemporary façade patterns in virtual reality: Influence of sky type, space function, and latitude

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A B S T R A C T
Recent studies have shown that the façade and light patterns in a space are an important factor in the occupants’ experience, but little is known about the generalizability of these findings in different lighting conditions, uses of space, or latitudes. This study employed virtual reality to investigate the effects of façade geometry and daylight patterns on space impressions and physiological responses (skin conductance, heart rate, and heart rate variability), while simultaneously examining the effect of sky type, spatial context, and latitude on participant responses. In an experimental study conducted in Switzerland and Greece, 256 participants were exposed to immersive interior scenes with six façade geometry variations with the same perforation ratio, derived from contemporary architecture. Participants evaluated the scenes under different sky types (clear sky with high or low sun angle, or overcast sky) and spatial contexts (working or socializing). The façade geometry influenced both the appraisal (how pleasant, interesting, exciting, or calming the space was perceived) and the visual appearance of the space (how complex, bright, or spacious the space was perceived). Façade geometry also influenced the reported satisfaction with the amount of view, with a façade variation with small, irregularly distributed openings driving this effect. Neither the sky type nor the spatial context influenced space impressions. Results showed a significant effect of country and an interaction between country and façade geometry only for ratings of excitement, with participants in Greece rating specific façade variations as more exciting than participants in Switzerland. Skin conductance level (logΔSCL) decreased under exposure to a social context in clear sky with a low sun angle compared to a working context in overcast sky conditions. No significant effects were found for the other physiological measures. The results of the present study show that façade geometry was the main driver of the participants’ spatial experience, inducing perceptual effects that were robust to variations in sky type and space function and to regional differences (except for excitement). These findings have implications for the built environment, delineating the façade geometry as an important design tool with a high application potential across lighting conditions and space uses, and across latitudes between central and southern Europe.

1. Introduction

While direct sunlight is often viewed as a source of visual discomfort, there is growing evidence that sunlight patterns are not only accepted, but even desired by occupants (Leather, Pyrgas, Beale, & Lawrence, 1998; Wymelenberg, Inanici, & Johnson, 2013). In particular, direct sun in one’s field of view has been related to visual interest (Parpairi, Baker, Steemers, & Compagnon, 2002; Rockcastle, Amundadottir, et al., 2017; Rockcastle, Amundadottir, & Andersen, 2017 a) and relaxation (Bou bekri, Hull, & Boyer, 1991), while the area of sunlight penetration has been related to well-being and job satisfaction (Leather et al., 1998). These positive perceptual effects of sunlight’s presence in a room have also been suggested to impact glare tolerance (Bou bekri & Boyer, 1992). Nevertheless, although several studies have examined the impact of

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continuous sunlight patches on human perception, little is known about how varying the diversity, size, shape, and distribution of sunlight patterns influence occupant responses, or about the perception of the façade configurations that create these patterns.

1.1. Effects of façade design on human perception

In agreement with lighting research, studies in the field of environmental psychology argue that a moderate level of sensory stimulation through intensity, variety, and complexity, is necessary for building occupants (Evans & McCoy, 1998). Similarly, Kaplan and Kaplan (1989) suggest complexity as an important predictor of landscape preference. This perspective is in line with Berlyne’s (1971) theory on stimulation, which stipulates that preference is a function of complexity, which in turn induces arousal. Berlyne (1971) proposed an inverted U-shape relationship between preference and complexity, with a medium level of complexity suggested as optimal and extreme levels of complexity being undesirable. This inverted U-shape relationship has been confirmed in experiments on the appraisal of abstract patterns (Friedenberg & Liby, 2016), paintings (Forsythe, Nadal, Sheehy, Cela-Conde, & Sawey, 2011; Saklofske, 1975), and images of nature (Spehar, Clifford, Newell, & Taylor, 2003; Taylor et al., 2005).

The notion of complexity is also important for theories in environmental psychology that aim to explain the beneficial effects of nature on recovery from stress. The Attention Restoration Theory (Kaplan, 1995; Kaplan & Kaplan, 1989) argues that natural environments have features that induce involuntary (rather than directed) attention, which contributes to restoration from mental fatigue resulting from prolonged and effortful attention. In a similar vein, the Stress Recovery Theory (Ulrich, 1983) asserts that contact with natural elements reduces psychophysiological stress through an immediate emotional response. These theories are particularly relevant for the fields of architecture and lighting design, as they focus on the features of the visual environment as drivers of psychological and physiological responses. These features are suggested to also be present in the built environment (Kaplan, Bardwell, & Slakter, 1993). The detail and ornamentation on a building’s façade have been identified as an important source of visual stimulation (Van den Berg, Joye, & Koole, 2016), and decorative patterns that schematically imitate natural elements are suggested to retain beneficial visual similarities with nature (Joye, 2007).

Contemporary architecture, contrary to modernism which has been heavily criticized for its lack of ornamentation, details, and patterns (Salingaros, 2014, 2017), shows a shift toward the use of multi-layered building envelopes, perforated walls, and decorative openings to filter the light that enters the space (Corrodi & Spechtenhauser, 2008). Although the impact of such patterned perforated façades on energy use and daylighting performance indoors has been widely investigated (Emami & Giles, 2016; Sabry, Sherif, Gadelhak, & Aly, 2014; Sherif, Sabry, & Rakha, 2010), current scientific knowledge regarding occupants’ perception and preference toward them is fragmented. In the present manuscript, the term ‘façade geometry’ will be used to indicate configurations of façade openings, which include fixed and movable shading systems (such as Venetian blinds), screens, perforated walls, or decorative openings.

Recent studies show that manipulations of façade geometry and of the resulting daylight patterns can impact both the impressions of the space, such as pleasantness and visual interest (Abboushi & Elzeyadi, 2018a, 2018b; Chamilothori, Chinazzo, et al., 2019; Chamilothori, Wienold, & Andersen, 2016; Omidfar, Niemann, & Groot, 2015), as well as the physiological responses of participants, such as their heart rate (Chamilothori, Chinazzo, et al., 2019). Although these studies outline a very promising research area, they lack a systematic and broad examination of façade characteristics, while in specific cases studies with similar stimuli show conflicting results (Abboushi & Elzeyadi, 2018a; Abboushi et al., 2019, 2021).

1.2. Missing knowledge in the perception of daylight spaces

In addition to the visual characteristics of the environment, space use is suggested to impact occupant preferences. Both the expected activity and the social scenario for an activity influence declared light preferences (Butler & Biner, 1987, 1989). Similarly, the expected space function (fictional scenarios of isolated work, teamwork, and relaxation) can affect the declared seating preference (Wang & Boubekeur, 2010). In the same vein, scenarios of using the same daylight space shown in virtual reality (VR) for working or socializing influenced how interesting and exciting the space was perceived (Chamilothori, Chinazzo, et al., 2019). However, most current knowledge about the relationship between space function and preference towards lighting conditions relies solely on scenarios presented through verbal instructions (Butler & Biner, 1987, 1989; Chamilothori, Chinazzo, et al., 2019), i.e., without the use of a corresponding visual stimulus or other indication of a change in the spatial context.

Another gap of knowledge regards the influence of lighting conditions on the experience of façade and daylight patterns. Previous studies in real environments used stimuli that change over time due to the varying daylight conditions (Abboushi et al., 2021; Abboushi & Elzeyadi, 2018a, 2018b), and thus might have confounding effects. On the other hand, studies in this domain that employ simulated environments, either immersive (Chamilothori, Chinazzo, et al., 2019; Omidfar & Sawyer & Chamilothori, 2019) or non-immersive (Abboushi, Elzeyadi, Taylor, & Sereno, 2019; Omidfar et al., 2015), and thus have full control over the characteristics of the presented stimuli, have largely been limited to the investigation of a single lighting condition. As a result, further research is necessary to investigate potential interactions between lighting conditions and spatial context, and to examine the robustness of façade-driven perceptual effects under different lighting conditions.

Recent recommendations for lighting research on human factors emphasize the importance of examining potential regional influences before assuming the generalizability of research findings across cultures (Veitch, Fotios, & Houser, 2019). Studies investigating the appraisal of artificial lighting, for instance, have found differences in the responses of participants from different continents (Liu, Luo, & Li, 2015; Park & Farr, 2007; Yoshizawa et al., 2015), though little is known about differences within smaller regions. Recent studies showed significant regional differences in the perception of window size variations in countries across Europe (Moscoso, Chamilothori, Wienold, Andersen, & Matusiak, 2021). On the other hand, field studies on visual discomfort found no difference that could be linked to geography between either neighboring countries or different continents (Pierson, Piderit, Iwata, Bodart, & Wienold, 2021). These conflicting findings raise the question of whether responses to façade and daylight patterns would vary between different countries. Thus, extending beyond typical demographic characteristics (such as age or gender), it is of interest to test the generalizability of findings and examine regional differences in the experience of façade geometry and corresponding light patterns.

Lastly, methodological recommendations in lighting research advise collecting involuntary physiological responses to complement recorded subjective responses (Veitch et al., 2019). Studies in real environments found that mean skin conductance response decreased under exposure to “relaxing lighting” compared to “strong lighting” with different color temperature and illumination levels (Izso, Lang, Laufer, Suplicz, & Horvath, 2009), showing lower physiological arousal levels under “relaxing lighting” conditions. On the other hand, experiments comparing VR scenes with different façade and light patterns found that the spatial context scenario, rather than the façade geometry, influenced skin conductance response, although façade geometry led to differences in how relaxing and exciting the space was perceived (Chamilothori, Chinazzo, et al., 2019). At the same time, façade geometry influenced mean heart rate, which decreased under exposure to an irregular façade variation compared to horizontal blinds. This finding could be explained...
by either an orienting effect towards the novel stimulus or an improved stress recovery from the potentially stressful condition at the beginning of the experiment (Chamilothori, Chinazzo, et al., 2019). In other cases, the presence of sunlight is confounded with other factors: recent studies in VR found that reported excitement increased while reported stress levels and skin conductance levels decreased when participants were shown a common area in an office with a window and plants under clear sky conditions compared to a windowless classroom without plants (Yin, Zhu, MacNaughton, Allen, & Spengler, 2018). This finding could be attributed to the presence of sunlight, plants, windows, the spatial context, or the interaction of these factors. To uncover the potential beneficial effects of façade and light patterns, and to differentiate the effects of façade geometry, lighting conditions, and spatial context, it is necessary to employ both subjective and physiological measures and to systematically test the influence of each factor.

1.3. Problem statement

Recent studies demonstrate that façade geometry and the corresponding sunlight patterns can have significant effects on occupants’ spatial experience and can even give rise to physiological responses, but are limited in the number and type of stimuli they examine. Moreover, existing studies employ either varying daylight conditions in a space with constant features, or varying façade features in constant lighting conditions, which does not allow for disentangling the effect of façade geometry and of daylight conditions on space appraisal. Lastly, the literature suggests that both the function of the space and the potential differences in occupant responses between regions are crucial in identifying the impact of façade geometry on occupants and generalizing these findings.

This article presents an experimental study that systematically investigates the impact of different façade and daylight patterns on the appraisal of space and the physiological responses of participants, addressing the aforementioned limitations by also examining the effects of spatial context and sky type on participant responses in two countries in Europe. To this end, we employ six façade geometry variations inspired by existing examples of contemporary architecture and manipulated to have an equal aperture ratio. The effect of sky type is investigated through three different conditions (a clear sky with a high sun angle, a clear sky with a low sun angle, and an overcast sky) which allows for comparison between different levels of sunlight penetration as well as the presence of direct versus only diffuse light, as the presence of sunlight patches has been related to impressions of visual interest (Rockcastle, Amundadottir, et al., 2017). The effect of spatial context is examined through two scenarios of space use (working or socializing), implied through changing the furniture of the presented scenes.

Lastly, we examine regional effects in the experience of daylight scenes by replicating the same study in Lausanne, Switzerland (latitude 46.53°) and Chania, Greece (latitude 35.51°), which are representative of the central and southernmost regions of Europe, respectively. To maintain full control of the experimental conditions across Europe, we employ immersive VR, which can adequately recreate the perception of real spaces (Abd-Alhamid, Kent, Bennett, Calautit, & Wu, 2019; Chamilothori, Wienold, & Andersen, 2019; Higuera-Trujillo, López-Tarruella Maldonado, & Llinares Millán, 2017). A subset of this experiment, with four façade geometry variations, was also repeated in Trondheim, Norway, representative of the northermost region in Europe, and an in-depth comparison of perceptual effects of daylight for the four common stimuli between these three latitudes can be found in (Chamilothori, Wienold, Moscoso, Matusiak, & Andersen, 2022). The present paper extends this work by investigating a richer stimulus set (six rather than four façade variations), testing the physiological responses of participants, and examining the interactions between the studied factors.

Following the aforementioned insights from the literature, the present study investigates the following hypotheses:

1. The experience of the space is influenced by the façade geometry.
2. The experience of the space is influenced by the sky type, with clear sky variations being perceived as more interesting and exciting than overcast sky conditions.
3. The experience of the space is influenced by the spatial context (working or socializing), with the social context being perceived as more pleasant and calming.

Considering the mixed findings regarding regional differences in the literature, we do not formulate explicit hypotheses for the effects of the factor country, but nevertheless examine its influence to determine the generalizability of our research findings in the two studied populations. Similarly, we examine two-way interactions between the factors façade geometry, sky type, spatial context, and country to identify such interaction effects and ensure that findings are interpreted correctly.

Furthermore, we investigate the effect of the factors façade geometry, sky type, spatial context, and their interactions on physiological responses (skin conductance, heart rate, and heart rate variability) in an exploratory manner, to complement the findings regarding the reported experience of the presented scenes. Skin conductance, heart rate, and heart rate variability (RMSSD, the root mean square of successive interbeat interval differences) have been suggested as indicators of activation of the sympathetic nervous system, of the parasympathetic and/or sympathetic nervous system (Cacioppo, Tassinary, & Berntson, 2007), and of the parasympathetic nervous system (Mejía-Mejía, Budidha, Abay, May, & Kyriacou, 2020), respectively. In particular, when related to emotional responses, skin conductance is thought to reflect changes in arousal and activation, while heart rate reflects changes in valence (Levenson et al., 2016). As previous studies have found that façade geometry influenced heart rate and ratings of excitement (Chamilothori, Chinazzo, et al., 2019), it is of interest to examine whether any identified perceptual effects of façade geometry, sky type, or context, are reflected in physiological responses.

In addition to these analyses, we explore differences and similarities in the experience of the different studied façade variations. By comparing different façade variations, we can investigate the effects of specific features, such as horizontal versus vertical stripes, or curvilinear elements, which have been related to impressions of naturalness (Berman et al., 2014) and have been widely established to be preferred over straight and angular elements (Gómez-Puerto, Munar, & Nadal, 2016). Lastly, we examine the relationship between the perceived complexity of façade geometry and pleasantness, which is expected to follow an inverted U-shaped curve (Berlyne, 1971).

2. Method

This study aims thus to examine the effect of façade geometry, sky type, spatial context, and country, as well as their interactions, on the experience and physiological responses towards a daylight interior space. In addition, we aim to identify façade variations that induce similar impressions, and to examine the relationship between perceived complexity and pleasantness.

2.1. Experimental conditions and materials

Six façade designs from contemporary architecture, shown in Fig. 1, were selected based on previous studies investigating the expected
perceptual effects of façade configurations according to architects (Chamilothori, Wienold, & Andersen, 2018). In particular, the selected variations were those exhibiting the strongest consensus among 20 contemporary façade designs about their potential to render a space the most calming (Fig. 1, Pattern 3), the least calming (Fig. 1, Pattern 5), the most exciting (Fig. 1, Pattern 4), and the least exciting (Fig. 1, Pattern 1) (Chamilothori et al., 2018). An additional façade variation with vertical stripes (Fig. 1, Pattern 2) from the same study was chosen to provide an example of a commonly used configuration alongside the horizontal stripes. A sixth variation (Fig. 1, Pattern 6) from Chamilothori et al. (2018) was selected as an example of a design that did not lead to a consensus amongst architects and had curvilinear openings, a feature that is crucial in visual perception (Levin, Takarae, Miner, & Keil, 2001) and has been linked to preference in both abstract patterns (Palumbo et al., 2020) and architectural interiors (Palumbo et al., 2020; Vartanian et al., 2013).

A multi-use room on the second floor of a building in the EPFL campus was selected as the reference space for the immersive scenes. The room, shown in Fig. 2, has a fully glazed east-facing façade along its length, a two-level ceiling, delineated with a row of concrete columns, and a wooden floor. This room was recreated in the Rhinoceros modeling software with dimensions of $10.9 \times 21.2$ m and a height of 3.4 m and 5.7 m at the low and high parts of the ceiling, respectively. All fixed objects in the room, such as luminaires, door and window handles, and columns, were modeled as well.

Each pattern was applied across the whole glazing in this space and edited to remove any visible seams or repetitions. Starting from the two-dimensional patterns from Chamilothori et al. (2018), each façade variation was modified to ensure a 40% ($\pm .1$) perforation ratio of open to total window surface. The 40% ratio was chosen to remain consistent with the original two-dimensional patterns, as well as façade variations used in related research (Chamilothori, Chinazzo, et al., 2019). Whenever possible, the dimensions of the individual openings were kept in a comparable range.1

To create the immersive scenes, physically-based renderings were generated using the Radiance simulation software (Ward Larson, 1994), following a validated workflow for the creation of perceptually accurate daylit scenes for VR (Chamilothori, Wienold, & Andersen, 2019). The Radiance material properties for the main surfaces and visual transmittance of the glazing were measured in the real environment and are described further in Section A1 of the Supplementary Material. Textures derived from photographs were applied to the floor and columns in the room to better represent the materials of the real space. To further enhance the realism of the scenes, an HDR photograph of the view out of the window (containing buildings, some greenery, and ground) was mapped to the Radiance sky and corrected to ensure similar luminance with the Radiance sky without mapping.

For the spatial context variations, two different sets of furniture were placed in the scene. A lounge setting with couches, tables, and chairs was used for the social context, and an office setting with desks, office chairs, and computers was used for the working context.

The resulting scenes were exported to Radiance using DIVA-for-Rhino and different sky types were created using gensky. Two variations of a clear sky type with sun were generated for the geographical coordinates of the Geneva area, with the same date (15/03) and varying time of day (10:36 and 9:00). These two clear sky type conditions were designed to correspond to a high sun angle that creates a restricted sunlight patch that does not fall on the furniture of the space and a low sun angle that allows sunlight penetration towards the depth of the room, with a solar altitude of 33.5° and 20.5°, respectively. In addition, an overcast sky type was created to provide diffuse daylight conditions.

The combination of façade variations, sky types, and spatial context produced 36 unique scenes, illustrated in Fig. 3, Fig. 4, and Fig. 5. Each scene was rendered from four different viewpoints corresponding to differences in participant height (explained further in Section A2 of the Supplementary Material), resulting in 144 simulations. A full 360° over-under stereo equirectangular projection of 12,960 × 12,960 pixels, shown in Fig. 6 (left), was simulated using the Radiance script view360Stereo.cal (Stock, 2017) and an interpupillary distance of 60 mm, and the Radiance parameters shown in Table A3 of the Supplementary Material. This projection method allows the creation of scenes that are fully immersive and stereoscopic, a substantial advantage over the projection methods used in previous VR studies (Chamilothori, Chinazzo, et al., 2019). More details about the image processing, tone-mapping, and photometric measurements of the resulting VR scenes can be found in Section A2 of the Supplementary Material. The

1 The individual elements in the different façade designs have a width of roughly 4–8 cm for Patterns 1, 2, 3, 4, and width from 4 up to 45 cm for Patterns 5 and 6, due to their design.
resulting images were used as textures in the Unity gaming engine and were perceived as stereoscopic from the participants’ perspective (Fig. 6, right).

An Oculus Rift CV1 VR headset was used to present the stimuli. Due to current technical limitations, the maximum luminance of the device measured at the level of the lens is 80 cd/m$^2$. The headset uses an OLED display with a resolution of 1080 × 1200 pixels per eye, a refresh rate of 90 Hz, and a 110° diagonal field of view.

2.2. Experimental design

This study followed a mixed 6x3x2x2 full factorial design. The design consisted of the within-subjects factor façade geometry (six façade geometry variations) and the between-subjects factors sky type (clear sky with high sun angle, clear sky with low sun angle, and overcast sky), spatial context (social and working context), and country (Switzerland and Greece). An overview of the factors and their levels can be found in Table 2. The façade geometry was employed as a within-subjects factor to
remove the variance due to differences between subjects, as this is the main factor of interest in the present study.

This study was part of a wider investigation that also examined the effect of window size on perception through another experimental phase. The two experimental phases were conducted in random order, with a break between them, and their presentation order was taken into account in the analysis to ensure no effect on participant responses. Further investigation of the effect of window size and space type on space perception can be found in Moscoso, Chamilothori, Wienold, Andersen, & Matusiak (2022).

2.3. Measures

2.3.1. Subjective responses

Regarding the affective appraisals of the presented scene, participants were asked how pleasant, interesting, exciting, and calming they found the space. These perceptual attributes are in line with previous studies in the literature that investigate the appraisal of daylit spaces.
(Amundadottir, Rockcastle, Sarey Khanie, & Andersen, 2017; Cauwerts, 2013; Moscoso & Matusiak, 2017) and aim to cover visual interest, as well as the positive and negative dimensions of valence and arousal (Russell, 1980).

In addition to the affective appraisals, we examined attributes that clearly relate to scalable aspects of the visual environment, following the categorization by Tiller and Rea (1992). Participants were asked to evaluate the perceived complexity of the space, an attribute that is expected to relate to the visual interest in the scene (Abboushi et al., 2019) and to influence aesthetic preference (Berlyne, 1971). In addition, we investigated the effect of façade geometry on the satisfaction with the amount of view in the space, as well as the perceived brightness and spaciousness of the scene, attributes which are directly related to view access (Franz, von der Heyde, & Bülthoff, 2005; Matusiak, 2006; Ozdemir, 2010; Stamps, 2010).

An overview of the dependent variables is presented in Table 1. Previous research showed that these attributes did not differ between real and 360° immersive virtual scenes (Abd-Alhamid, Kent, Calautit, &
wrist electrodes of an 8 mm diameter contact area. The EDA data were measured with a sampling rate of 4 Hz via two dry ventral electrodes of an 8 mm diameter contact area. The EDA data were E4 wristband device (Garbarino, Lai, Bender, Picard, and Tognetti, 2014) worn on the left hand of the participant. Participants remained silent and standing during both baseline and stimulus exposure measurements. As discussed in Section 1.3, the activation of the autonomic nervous system was examined using electrodermal activity, heart rate, and heart rate variability measures. Electrodermal activity (EDA), blood volume pulse data (BVP), and heart rate (HR) were collected with an Empatica E4 wristband device (Garbarino, Lai, Bender, Picard, & Tognetti, 2014) worn on the left hand of the participant. Participants remained silent and standing during both baseline and stimulus exposure measurements.

EDA was measured with a sampling rate of 4 Hz via two dry ventral wrist electrodes of an 8 mm diameter contact area. The EDA data were separated into phasic and tonic components using the continuous decomposition analysis model of the Ledalab toolbox (v.3.4.9) (Benedek & Kaernbach, 2010) in MATLAB using default filtering, smoothing, and optimization settings. The mean skin conductance level (SCL) and the number of skin conductance responses (nSCRs) were selected as measures of tonic and phasic sympathetic activation, respectively. Both measures were computed for a response window of 1–4 s after stimulus exposure, and nSCR was calculated using a minimum amplitude threshold of 0.01 μS (Dawson, Schell, & Filion, 2007). To account for individual differences in electrodermal activity, SCL and nSCRs for each stimulus exposure were subtracted from the equivalent baseline measurement for that participant, resulting in ΔSCL and ΔnSCR, respectively.

BVP was recorded through photoplethysmography sensors with a sampling rate of 64 Hz and was used to derive interbeat interval (IBI) data using the BioSPPy Python software (Carreiras et al., 2015), following previous research using the same device (Dzieżyck et al., 2021). The resulting IBI data were examined for spuriously short or long IBIIs (Overbeek, van Boxtel, & Westerink, 2014) and either discarded (59.1% of the data) or corrected manually as described in Section A4 of the Supplementary Material. In total, 432 from a total of 28,315 valid IBI data points were corrected. The resulting IBI data were used to compute the root mean square of successive differences between heartbeats (RMMSD) for the first 30 s of stimulus exposure, a measure of heart rate variability shown to be reliable for such short measurement periods (Baek, Cho, Cho, & Woo, 2015). HR data from Empatica E4 are derived from BVP with a sampling rate of 1 Hz using Empatica’s proprietary algorithm, where it is computed as the average heart rate of the preceding 10 s. As a result, the mean HR for each stimulus was calculated for the period from 11 s to 30 s after stimulus exposure. HR data were examined using the same thresholds as for IBI (HR = 60000/IBI) and no problematic cases were identified. Both RMMSD and mean HR were subtracted from the corresponding baseline measures of each participant, and are thus referred to as ΔRMSSD and ΔHR, respectively.

Participants were recruited via e-mail and posters. Participation was voluntary and eligible participants were selected based on criteria of normal or corrected-to-normal vision, age between 18 and 50 years old, English language proficiency of C1 or higher, and a minimum duration of stay of 18 months in the country where the experiment took place. The age restriction was applied to avoid the occurrence of presbyopia (Brückner, 1967) which is problematic for head-mounted displays. In addition, the minimum duration of stay ensured regional adaptation,

Table 1
Overview of subjective responses collected in the study.

| How pleasant is this space? | How interesting is this space? | How exciting is this space? | How complex is this space? | How bright is this space? | How spacious is this space? | How satisfied are you with the amount of view in this space? |
|----------------------------|-------------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------------------------------------------------------|
| How pleasant is this space? | How interesting is this space? | How exciting is this space? | How complex is this space? | How bright is this space? | How spacious is this space? | How satisfied are you with the amount of view in this space? |
| Switzerland                | Greece                        | Switzerland                | Greece                    | Switzerland                | Greece                    | Switzerland                |

Table 2
Sample size per country, spatial context, and sky type.

| Sky type          | Social context | Work context | Social context | Work context |
|-------------------|----------------|--------------|----------------|--------------|
| Clear, high sun   | 20             | 20           | 21             | 23           |
| Clear, low sun    | 20             | 20           | 27             | 23           |
| Overcast sky      | 18             | 20           | 22             | 22           |
| Total             | 58             | 60           | 70             | 68           |
following the threshold of 18 months of stay for a satisfactory adjustment in a foreign country (Lynggaard, 1955).

From an initial sample size of 265 participants, 9 were excluded as they did not fulfill the required criteria. The resulting sample size thus corresponded to 256 participants: 118 in Switzerland (58 women and 60 men) and 138 in Greece (64 women and 74 men). Participant age ranged from 20 to 50 years in Switzerland ($M = 27.4$ years, $SD = 7.4$ years) and from 19 to 44 years in Greece ($M = 24.2$ years, $SD = 4.7$ years). Concerning their country of origin, 30% and 94% of participants in Switzerland and in Greece reported the same country of origin as the country of study, respectively. Regarding their training, 90% of participants in Switzerland and 59% of participants in Greece reported no training in either architecture, lighting design, or VR. The percentage of participants in Switzerland and in Greece reporting having been trained in one of these areas was, respectively, 8% and 35% for architecture, 0% and 4% for lighting, and 2% for VR (both countries).

Participants in each country were randomly assigned to one of six conditions corresponding to the combination of the factors sky type and spatial context. Table 2 presents the distribution of participants to each unique condition.

Physiological data were not collected for eight participants in Greece and one in Switzerland due to technical issues with the device. As a result, the sample size for ASCL, ΔSCR, and ΔHR was 130 participants in Greece and 117 in Switzerland, and for ΔMSSD, for which a substantial part of the data was discarded, as discussed earlier, 68 participants in Greece and 77 in Switzerland. In addition, the physiological data corresponding to five stimuli in Switzerland and 18 stimuli in Greece were discarded due to problematic conditions for data quality (such as the participant speaking during the silent exploration period).

This experimental study was approved by the EPFL Human Research Ethics Committee (applications 008–2016 and 025–2017) and complied with the tenets of the Declaration of Helsinki. Participants provided written informed consent before the beginning of the experiment and were compensated for taking part in the study with 10 Swiss Francs or Euros, depending on the country.

### 2.5. Experimental protocol

Experiments in Greece and Switzerland were conducted in May 2018 and June 2018, respectively. Sessions took place in office rooms in the Technological University of Cretecampsus (Greece) and in the EPFL campus (Switzerland) that were selected to ensure a quiet experimental space with commonly found indoor environmental conditions. An Onset U12 HOBO Logger was used to record air temperature and humidity. Measurements showed that air temperature ranged from $21.6 \text{ °C}$ to $29.7 \text{ °C} (M = 25 \text{ °C}, SD = 7.7 \text{ °C})$ in Switzerland and from $22.6 \text{ °C}$ to $27.9 \text{ °C} (M = 24.4 \text{ °C}, SD = 3.8 \text{ °C})$ in Greece, and relative humidity ranging from 31.2% to 69.5% ($M = 55.8\%$, $SD = 17.9\%$) in Switzerland and from 35.5 to 73.4% ($M = 55.5\%, SD = 10.3\%$) in Greece, indicating similar conditions between the two countries.

The experiment took place in individual sessions of 25 min on average. Participants were first welcomed and presented with information about the experiment. If they consented to the experiment, participants were provided with the written definitions of the studied attributes, were introduced to the equipment, and the Empatica E4 device was placed on their left hand by the experimenter.

Participants were first asked to answer the demographic questions and were requested to provide their height, which was used to select the equivalent VR viewpoint. Next, they were shown how to adjust the headset in a training scene with a black background and white letters, and were instructed to remain in the same spot and explore the scene by turning around. After wearing the headset, participants remained standing for the remaining duration of the experiment, including the presentation of the stimuli and the verbal questionnaire.

Before the presentation of each immersive scene, a single color was displayed in VR for 15 s to ensure chromatic adaptation (Rinner & Gegenfurtner, 2000). This color corresponded to the average RGB value of the scenes that would be shown to the participant. When presented with the first experimental scene, participants were told to imagine they were working or socializing in the scene, in accordance with the spatial context. Participants were asked to remain silent for the first 30 s of presentation of each new immersive scene while they could freely explore the virtual environment by looking around while remaining in the same spot. When participants were ready, they answered the verbal questionnaire for the presented scene while remaining immersed in the virtual environment. The same procedure was followed until the end of the experiment, with the single color scene preceding each presented scene and a silent period during the first 30 s of exposure to each scene. Each participant saw all six façade variations (within-subjects factor) in random order in a randomly allocated combination of a particular sky type and spatial context (between-subjects factors).

### 2.6. Statistical analysis

Repeated measures from the same participant were collected for each level of the factor façade geometry. To avoid the violation of the assumption of independence between observations, we employ Linear Mixed Models (LMM), which address the issue by taking into account the correlated structure of the data (McCulloch & Searle, 2001). The full dataset is available upon request to the authors.

Linear mixed model analyses were conducted with the statistical software R (R Core Team, 2018) and the R packages lme4 (Bates, Mächler, Bolker, & Walker, 2015, p. 4) and lmerTest (Kuznetsova, Christensen, & Moahl, 2017). Separate linear mixed model analyses were conducted for each dependent variable. The façade geometry, sky type, spatial context, country, and the interactions between these factors, façade geometry*sky type, façade geometry*spatial context, sky type*spatial context, country*façade geometry, country*sky type, and country*spatial context, were used as fixed effects. Whenever the interaction term did not meet our significance threshold, it was excluded from the final model.2 The unique identification number of each participant was specified as a random intercept to account for the possible correlation between responses of the same subject, as well as for the inter-subject variance in responses. Analyses were controlled for the potential confounding factors of the participants’ gender, first presented façade variation, and experimental phase order by specifying them as covariates in the model. All factors were specified as categorical variables in R.

Variance Inflation Factors (VIF) were below the commonly used threshold of 10 (Belsley, 2004). The visual inspection of residual plots showed that assumptions of homoscedasticity and normality were respected, except for the model for perceived spaciousness, which deviated from normality. However, simulation studies in the literature show that LMM is robust when this assumption is not followed (Maas & Hox, 2004), especially with a high number of groups as is the case in our study.

The statistical significance of the effect of each term was calculated using type III Wald F tests with the Kenward-Roger method using the R package car (Fox & Weisberg, 2011). This method was selected because it is robust to data with low skewness and high kurtosis, especially for sample sizes larger than 45 (Arnaud, Bendayan, Blanca, & Bon, 2013), which is the case of our dataset with a total sample size of 256, and a skewness ranging from $-0.03$ (perceived complexity) to $-0.43$ (perceived pleasantness) and a kurtosis ranging from 2.3 (satisfaction with the amount of view) to 3.10 (perceived spaciousness) for the subjective dependent variables. For the physiological responses, skewness and kurtosis were $-0.66$ and 3.06, respectively, for ΔSCR, 2.87 and

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2 The specification of the final models (without interactions) was as follows: Dependent variable ~ FACADEGEOMETRY + SKYTYPE + SPATIALCONTEXT + COUNTRY + GENDER + FirstPatternShown + ExperimentalPhaseOrder + (1|Participant).
26.01 for $\Delta$SCL, $-0.97$ and 6.95 for $\Delta$HR, and lastly $-0.27$ and 3.20 for $\Delta$RMSSD. To reduce the kurtosis for $\Delta$SCL, the data were log-transformed (Dawson et al., 2007) after the addition of a constant to ensure that the minimum $\Delta$SCL value would be equal to 1, resulting in a skewness of $-2.18$ and a kurtosis of 15.67. The log-transformed data, which will be referred to as log$\Delta$SCL, remain extremely leptokurtic after the transformation. Since the Kenward-Roger method is robust to kurtosis values of 12 for group sizes of 20 (Aarnou, Bendayan, Blanca, & Bono, 2014), as in the present study, it was decided to proceed with the log-transformed data (Dawson et al., 2007) after the addition of a constant to $\Delta$RMSSD. To reduce the kurtosis for $\Delta$SCL, which will be referred to as log$\Delta$SCL, 26.01 for $\Delta$SCL, $-0.97$ and 6.95 for $\Delta$HR, and lastly $-0.27$ and 3.20 for $\Delta$RMSSD, showing that a substantial proportion of the variance is accounted for the multiple comparisons of 8 models as we consider these to belong to one family of tests. In the case of a significant effect of the main factors, post-hoc pairwise comparisons of estimated marginal means were conducted using the R package emmeans v.1.3.2 (Lenth, 2019) and applying the Sidák correction for multiple comparisons (Sidak, 1967). A simulation-based sensitivity analysis using the R package simr (Green & MacLeod, 2016) showed that our design had a statistical power of 80% 

### Table 3

Results of the LMM analysis for the main factors of interest Country, Façade geometry, Spatial context, and Sky type on all subjective responses.

| Predictor     | Attribute | df  | F    | p-value |
|---------------|-----------|-----|------|---------|
| Country       | Pleasant  | 1, 242.95 | 0.20 | 0.66    |
| Interest      | Interesting | 1, 242.99 | 2.17 | 0.14    |
| Exciting      | Exciting | 1, 712.54 | 13.77 | 0.002  |
| Calming       | Calming | 1, 242.94 | 1.72 | 0.19    |
| Complex       | Complex | 1, 242.98 | 0.29 | 0.59    |
| Bright        | Bright | 1, 243.02 | 4.25 | 0.04    |
| Spacious      | Spacious | 1, 243.05 | 1.35 | 0.24    |
| View$^*$      | View$^*$ | 1, 242.98 | 2.91 | 0.09    |
| Façade geometry | Façade geometry | 5, 1275.82 | 15.64 | <0.00001 |
| Interest      | Interesting | 5, 1275.74 | 64.99 | <0.00001 |
| Exciting      | Exciting | 5, 1275.74 | 52.60 | <0.00001 |
| Calming       | Calming | 5, 1275.82 | 19.21 | <0.00001 |
| Complex       | Complex | 5, 1275.76 | 132.15 | <0.00001 |
| Bright        | Bright | 5, 1275.66 | 43.03 | <0.00001 |
| Spacious      | Spacious | 5, 1275.58 | 8.98  | <0.00001 |
| View$^*$      | View$^*$ | 5, 1275.75 | 82.07 | <0.00001 |
| Spatial context | Spatial context | 1, 256.85 | 2.49 | 0.12    |
| Interest      | Interesting | 1, 261.59 | 0.20 | 0.65    |
| Exciting      | Exciting | 1, 261.35 | 0.72 | 0.40    |
| Calming       | Calming | 1, 256.50 | 1.27 | 0.26    |
| Complex       | Complex | 1, 260.43 | 1.27 | 0.26    |
| Bright        | Bright | 1, 266.62 | 0.10 | 0.75    |
| Spacious      | Spacious | 1, 271.78 | 0.69 | 0.40    |
| View$^*$      | View$^*$ | 1, 261.02 | 1.14 | 0.85    |
| Sky type      | Sky type | 2, 253.23 | 0.94 | 0.39    |
| Interesting   | Interesting | 2, 257.10 | 1.21 | 0.30    |
| Exciting      | Exciting | 2, 259.92 | 1.33 | 0.27    |
| Calming       | Calming | 2, 253.32 | 0.81 | 0.44    |
| Complex       | Complex | 2, 356.22 | 0.53 | 0.59    |
| Bright        | Bright | 2, 260.94 | 1.68 | 0.18    |
| Spacious      | Spacious | 2, 264.91 | 0.48 | 0.62    |
| View$^*$      | View$^*$ | 2, 256.67 | 0.16 | 0.85    |
| Façade geometry*Country | Façade geometry*Country | 5, 1270.74 | 3.36 | 0.005 |

$^*$ Satisfaction with the amount of view.

### Table 4

Marginal and conditional R$^2$ of the LMM for each subjective response variable.

| Dependent variable | $R^2_{\text{marginal}}$ | $R^2_{\text{conditional}}$ |
|--------------------|------------------------|-----------------------------|
| Pleasantness       | 0.05                   | 0.38                        |
| Interest           | 0.14                   | 0.53                        |
| Excitement         | 0.14                   | 0.53                        |
| Calmness           | 0.06                   | 0.38                        |
| Complexity         | 0.23                   | 0.56                        |
| Brightness         | 0.10                   | 0.60                        |
| Spaciousness       | 0.06                   | 0.65                        |
| Satisfaction       | 0.16                   | 0.53                        |

Ferguson (2009), where an $R^2$ of 0.25 is considered moderate and an $R^2$ of 0.64 is considered strong, these conditional $R^2$ values can be interpreted as moderate-to-strong for all attributes except spaciousness, and as strong in the case of perceived spaciousness.

Façade geometry influenced all subjective responses, confirming our first hypothesis. Specifically, the façade geometry influenced how pleasant ($F(5, 1275.82) = 15.64, p < 0.0001$), interesting ($F(5, 1275.74) = 64.99, p < 0.0001$), exciting ($F(5, 1270.74) = 21.24, p < 0.0001$), and spacious ($F(5, 1275.82) = 19.21, p < 0.0001$) the space was evaluated. Regarding the visual appearance of the space, the façade geometry affected how complex ($F(5, 1275.76) = 132.15, p < 0.0001$), bright ($F(5, 1275.66) = 43.03, p < 0.0001$), and spacious ($F(5, 1275.58) = 8.98, p < 0.0001$) the scene was perceived. Lastly, the façade geometry influenced the satisfaction with the amount of view in the space ($F(5, 1275.75) = 82.07, p < 0.0001$). Figs. 7 and 8 show the mean ratings and standard deviations per studied attribute for each façade geometry across all variations of sky type, spatial context, and country. The façade variations are represented with the corresponding

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$^*$ The specification of the null (intercept only) models was as follows: DependentVariable $- 1 + (1|Participant)$. 

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pattern from Fig. 1 for readability, and they will be referred to as “Pattern [X]” with numbers from one to six, one being the leftmost and six being the rightmost.

Neither the factor sky type (all ps > .18) nor the spatial context (all ps > .12) affected the participants’ responses in the studied variables, and thus our second and third hypotheses were rejected.

Regarding regional differences, the evaluation of how exciting the space was perceived differed significantly between the two countries (F(1, 712.54) = 13.77, p = .002; all other ps > .09). Pairwise comparisons showed that participants in Greece rated the scenes as more exciting (EMM = 5.28, SE = 0.13, 95% CI [5.02, 5.53]) than participants in Switzerland (EMM = 4.75, SE = 0.14, 95% CI [4.47, 5.02]). Results showed a significant interaction between country and façade geometry for ratings of excitement (F(5, 1270.74) = 3.36, p = .005). Follow-up pairwise comparisons showed that responses between the two countries differed only for Pattern 1 ($B = 0.96$, p = .0002), Pattern 2 ($B = 0.61$, p = .02), and Pattern 3 ($B = 0.89$, p = .0006) (all other ps > .17). In particular, participants in Greece rated these façade variations as more exciting (Pattern 1: EMM = 4.62, SE = 0.18, 95% CI [4.28, 4.97], Pattern 2: EMM = 4.54, SE = 0.18, 95% CI [4.20, 4.89], Pattern 3: EMM = 5.71, SE = 0.18, 95% CI [5.37, 6.05]) than participants in Switzerland (Pattern 1: EMM = 3.67, SE = 0.19, 95% CI [3.29, 4.04], Pattern 2: EMM = 3.94, SE = 0.19, 95% CI [3.57, 4.31], Pattern 3: EMM = 4.82, SE = 0.19, 95% CI [4.45, 5.19]).

3.2. Perceptual differences between façade characteristics

To further investigate the effect of façade geometry on subjective responses, post-hoc pairwise analyses were conducted for all combinations of façade geometry variations for each subjective response variable. Estimated marginal means and standard errors are provided in Table A4 of the Supplementary Material.

As the pairwise comparisons are too many to be depicted in a figure, Tables 5–9 present the results in a matrix for each subjective response variable. These tables are conceptually similar to a correlation matrix and allow the reader to observe clusters and trends in the results. Pairs with significant differences between them are reported with the relevant estimates. For brevity, outcomes will be described in text only when discussing a particularly notable finding.

3.2.1. Ratings of pleasantness

Table 5 shows that Patterns 3 and 6 were similar in terms of how pleasant the space was evaluated, as they led to significantly higher ratings compared to Patterns 1, 2, 4, and 5, while they did not differ between them. Specifically, Pattern 3 led to a maximum estimated increase of 9% in the 11-point rating scale for perceived pleasantness ($B = 1.02$, p < .0001) compared to Pattern 4. Scenes with Pattern 4 were also evaluated as less pleasant compared to those with Pattern 1 ($B = 0.47$, p = .02) and Pattern 5 ($B = 0.56$, p = .002). Lastly, Patterns 1 and 2 did not differ significantly between them.
3.2.2. Ratings of interest

Regarding ratings of interest, Table 5 shows that Patterns 1 and 2 induced similar responses, as both led to lower evaluations compared to Patterns 3, 4, 5, and 6. In particular, Pattern 1 induced a maximum estimated decrease of 16% in interest ($B = 1.80, p < .0001$) when compared to Pattern 6. Patterns 5 and 6 have analogous results, as both variations were rated as more interesting than Patterns 1, 2, 3, and 4. In combination with the lack of significant differences within specific pairs, this finding suggests three clusters of façade variations: Patterns 1 and 2, Patterns 3 and 4, and Patterns 5 and 6, inducing responses of low, moderate, and high interest, respectively.

3.2.3. Ratings of excitement

The paired comparisons for excitement, shown in Table 6, are separated for each country due to the significant interaction between country and façade geometry. The results show the same clustering of façade variations for Patterns 1 and 2 and Patterns 5 and 6 as for perceived interest for both countries. However, Pattern 3 differed from Pattern 4 in excitement for Greece, but not for Switzerland. At the same time, Pattern 3 led to higher ratings of excitement compared to Patterns 5 and 6 in Switzerland, but not for Greece. The maximum difference in ratings of excitement is found between Patterns 1 and 6 in Switzerland, with a decrease of 18.7% ($B = -1.09, p < .0001$) from Pattern 1 to 6, and between Patterns 2 and 6 in Greece, with a decrease of 11.5% ($B = -1.27, p < .0001$) from Pattern 2 to 6.

3.2.4. Ratings of calmness

Table 7 shows that once again, Patterns 1 and 2 did not differ in how calming the space was perceived. Pattern 3 led to the highest ratings of calmness, being evaluated higher than all patterns except for Pattern 1, with a maximum estimated increase of 10% ($B = 1.09, p < .0001$) compared to Pattern 5. As for pleasantness, differences are found between Patterns 5 and 6. Lastly, Pattern 6 led to the space being evaluated as more calming compared to Patterns 4 and 5, and as less calming compared to Patterns 1 and 3.

3.2.5. Ratings of complexity

Table 8 shows three clusters of façade variations of low, moderate, and high perceived complexity. Specifically, the absence of significant differences between Patterns 1 and 2, as well as between Patterns 4, 5, and 6, suggests two groups of façade variations with similarly perceived complexity within each group. Pattern 3 led to higher ratings of complexity compared to Patterns 1 and 2, and also to lower ratings compared to Patterns 4, 5, and 6, suggesting that this variation was a stimulus of moderate perceived complexity in the present study. Lastly, Patterns 1 and 2 are evaluated as less complex than Patterns 3, 4, 5, and 6, with a maximum estimated decrease of 21% in perceived complexity ($B = -2.34, p < .0001$) between Patterns 1 and 5.

Fig. 9 shows the relationship between mean ratings of complexity and pleasantness to examine whether the commonly found inverted U-shaped relationship, with moderately complex stimuli being perceived as more pleasant than stimuli low or high in complexity, is also replicated in the present study. The results are in line with the literature, except for Pattern 4, which does not differ in perceived complexity from Patterns 5 and 6 but leads to significantly lower ratings of pleasantness compared to these façade geometry variations (see Table 5).
3.2.6. Ratings of brightness, spaciousness, and satisfaction with the amount of view

Tables 8 and 9 show that Pattern 4 was the main driver of the effect of façade geometry on the perceived brightness, spaciousness, and satisfaction with the amount of view. Pattern 4 led to lower evaluations of how pleasant and interesting the space was perceived. Estimates B (comparison: column minus row), standard errors (SE), and p-values are shown for pairs with significant differences.

Table 5
Pairwise comparisons of all façade variations for the evaluations of how pleasant and interesting the space was perceived. Estimates B (comparison: column minus row), standard errors (SE), and p-values are shown for pairs with significant differences.

| How pleasant is this space?          |
|--------------------------------------|
| Pattern 1                           |
| Pattern 2                           |
| Pattern 3                           |
| Pattern 4                           |
| Pattern 5                           |
| Pattern 6                           |

| How interesting is this space?      |
|-------------------------------------|
| Pattern 1                          |
| Pattern 2                          |
| Pattern 3                          |
| Pattern 4                          |
| Pattern 5                          |
| Pattern 6                          |

Significance levels are marked as follows: * = p<0.05, ** = p<0.01, *** = p<0.001, **** = p<0.0001.

3.3. Effects of façade geometry, sky type, spatial context, and country on physiological responses

Interaction terms were not significant for ΔnSCR (all ps >.27), ΔHR (all ps >.21), or ΔRMSSD (all ps >.11) and were thus removed from the models. The interaction between sky type and context was significant for logΔSCL (ps >.52 for the other interaction terms) and thus was included in the final model.

Subsequent analyses on the final ΔnSCR model without interaction terms showed no significant effects of façade geometry, sky type, context, or country on ΔnSCR (all ps >.32). Regarding logΔSCL, the interaction sky type*context (F(2, 241.56) = 3.83, p = .023) as well as the factors sky type (F(2, 247.99) = 3.22, p = .041) and context (F(1, 233.41) = 4.48, p = .035) influenced logΔSCL. Façade geometry (F(5,1213.33) = 2.20, p = .05) approached significance, and country was not significant (p=.60).

Considering the presence of interactions, post-hoc comparisons were conducted for all combinations of the factors sky type and context. These analyses showed a significant difference in logΔSCL only between the clear sky with low sun angle in the social context condition (EMM = 2.58, SE = 0.04, 95% CI [2.50, 2.67]) compared to the overcast sky in the working context condition (EMM = 2.75, SE = 0.05, 95% CI [2.66, 2.84]), with the former leading to a significant decrease in logΔSCL (B = −0.16, p = .029) (all other ps >.16). R² conditional were 0.01 and 0.52, respectively, for the logΔnSCR model, and 0.06 and 0.89 for the logΔSCL model.

No significant effects were found for façade geometry, sky type, spatial context, or country on ΔRMSSD (all ps >.27) or ΔHR (all ps >.19). R² marginal and R² conditional were 0.07 and 0.70, respectively, for the ΔRMSSD model, and 0.04 and 0.54 for the ΔHR model.

3.4. Effects of potential confounding factors

Regarding the effects of potential confounding factors, the presentation order of the experimental phases did not influence the participant responses for any of the subjective (all ps >.029) or physiological (all ps >.19) responses. The first façade variation that was presented influenced only perceived complexity (F(5, 251) = 0.39, p = .006) (all other ps >.021 for subjective responses and ps >.14 for physiological responses). Post-hoc comparisons for perceived complexity showed...
Table 6
Pairwise comparisons of all façade variations for the ratings of how exciting and calming the space was perceived. Estimates $B$ (comparison: column minus row), standard errors (SE), and p-values are shown for pairs with significant differences.

| Pattern | How exciting is this space? (Switzerland) |
|---------|------------------------------------------|
| Pattern 1 | ![Image] |
| Pattern 2 | ![Image] |
| Pattern 3 | ![Image] |
| Pattern 4 | ![Image] |
| Pattern 5 | ![Image] |
| Pattern 6 | ![Image] |

| Pattern | How exciting is this space? (Greece) |
|---------|-------------------------------------|
| Pattern 1 | ![Image] |
| Pattern 2 | ![Image] |
| Pattern 3 | ![Image] |
| Pattern 4 | ![Image] |
| Pattern 5 | ![Image] |
| Pattern 6 | ![Image] |

Significance levels are marked as follows:
* $= p<0.05$, ** $= p<0.01$, *** $= p<0.001$, **** $= p<0.0001$.

Table 7
Pairwise comparisons of all façade variations for the ratings of how calming the space was perceived. Estimates $B$ (comparison: column minus row), standard errors (SE), and p-values are shown for pairs with significant differences.

| Pattern | How calming is this space? |
|---------|------------------------------|
| Pattern 1 | ![Image] |
| Pattern 2 | ![Image] |
| Pattern 3 | ![Image] |
| Pattern 4 | ![Image] |
| Pattern 5 | ![Image] |
| Pattern 6 | ![Image] |

Significance levels are marked as follows:
* $= p<0.05$, ** $= p<0.01$, *** $= p<0.001$, **** $= p<0.0001$. 
significant differences only between two pairs of façade geometry variations: when Pattern 1 was presented first, complexity ratings were on average lower compared to when Pattern 2 was presented first ($B = -1.92, p = .004$), and when Pattern 2 was presented first, complexity ratings were higher compared to when Pattern 6 was presented first ($B = 1.08, p = .001$) (all other $ps > .08$).

Lastly, gender influenced participant ratings solely for the satisfaction with the amount of view ($F(1, 255) = 7.97, p = .005, all other $ps > .039$), with female participants reporting lower satisfaction with the amount of view ($EMM = 4.95, SE = 0.15, 95\% \text{ CI} [4.66, 5.25]$) than male participants ($EMM = 5.53, SE = 0.14, 95\% \text{ CI} [5.25, 5.81]$). Gender also influenced $\Delta$RMSSD ($F(1, 137.44) = 7.91, p = .006$), with female participants showing a higher $\Delta$RMSSD ($EMM = 63.7, SE = 8.03, 95\% \text{ CI} [47.8, 79.6]$) than male participants ($EMM = 33.8, SE = 7.44$).
No effects of gender were found for $\Delta n$SCR, log$\Delta SCL$, or $\Delta HR$ (all $p$s $> .12$).

**4. Discussion**

### 4.1. Overview of key findings and comparison with the literature

Participants in Switzerland and Greece were exposed to variations in the façade geometry, the sky type, and the spatial context of a daylit VR scene. The presented façade geometry significantly influenced the subjective evaluations for all studied attributes, confirming our hypothesis and in alignment with previous research (Abboushi et al., 2019; Chamilothori, Chinazzo, et al., 2019). However, neither the sky type nor the spatial context that was experienced by each participant influenced the experience of space, contrary to our expectations.

The studied country did not influence participant responses, except for ratings of excitement where participants in Greece rated the scenes more positively than participants in Switzerland. These results are in line with previous research on regional differences in the perception of different window sizes, where ratings of excitement differed between participants in Greece, Switzerland, and Norway, and scenes were rated as more exciting by participants in Greece than in Switzerland (Moscoso...
et al., 2022). The same study found that participants in Greece evaluated scenes with façade variations as brighter than participants in Norway (Moscoso et al., 2022); this effect was however not found between participants in Greece and Switzerland. Although this finding does not apply to all studied attributes, the direction of these effects suggests a potential trend of participants in Greece responding more positively. Additional research is needed to further explore this possibility.

Analyses of skin conductance measures showed a significant main effect of sky type and of context and a significant interaction between sky type and context for logASCL. In particular, logASCL decreased under exposure to scenes depicting a clear sky with a low sun angle and furniture of a lounge compared to those depicting an overcast sky and an open plan office. This finding demonstrates lower sympathetic activation in the combined presence of large sun patches and a social context and indicates a potential calming effect of this condition. A follow-up comparison between these two conditions in perceived calmness (although the interaction sky type*context did not meet our significance threshold) was in agreement with this finding, with the clear sky with low sun angle and social context being perceived as more calming than the overcast sky and working context (B = 0.72, p = .01). The significant decrease in SCL between a sunny common room with plants and a windowless classroom without plants found in Yin et al. (2018) is in line with these results and could potentially be attributed to the interaction between lighting conditions and spatial context. Nevertheless, these results should be interpreted with caution due to the high kurtosis of the logASCL data. No significant effects of façade geometry, sky type, context, or country were found for either ΔnSCR, ΔRMSSD, or ΔHR. The absence of a significant effect for façade geometry is in alignment with the literature for ΔnSCR, but not for ΔHR, which differed between façade geometry variations in previous research (Chamilothori, Chinazzo, et al., 2019). However, in Chamilothori, Chinazzo, et al. (2019) participants were not instructed to remain silent during exposure to the stimuli, and thus outcomes might not be comparable and warrant further investigation.

Lastly, gender unexpectedly influenced the reported satisfaction with the amount of view, with female participants rating their satisfaction as lower than male participants. Previous research has found that female participants evaluated a space more negatively than male participants regarding, for example, the lighting, privacy, or spaciousness of the room (Yildirim, Akalin-Baskaya, & Celebi, 2007). However, in the present study, this difference was only found for the satisfaction with the amount of view. To our knowledge, gender effects on satisfaction with the view and on view quality have not been investigated, and thus our findings show that this topic merits further investigation.

The finding that the façade geometry was the only factor that consistently influenced the participants’ impressions of the space is particularly relevant for the application of the findings in the built environment, as it places the focus on the design of the façade as a tool to shape the experience of the space. As a result, the findings of this study regarding the effects of façade variations can complement a designer’s intuition and contribute to façade designs that are likely to induce specific subjective impressions in their occupants.

4.2. Perceptual effects of specific façade geometry variations

Findings reveal that specific pairs of façade geometry variations led to similar effects in the occupants’ experience of the space. Patterns 1 and 2 (vertical and horizontal stripes) did not differ between them for any of the studied attributes, while Patterns 5 and 6, two of the most complex façade geometry variations, only differed in how pleasant and calming the space was evaluated. In addition, Patterns 5 and 6 were rated as more complex and more exciting than Patterns 1 and 2. As the studied sky types did not influence the experience of the space, the aforementioned differences in perceived excitement and complexity can be attributed to the complexity of the façade composition itself, rather than of the resulting sunlight pattern.

Scenes with Patterns 5 and 6 were also evaluated as significantly more interesting than all other variations. These findings are in alignment with the results of previous studies on the perception of façades with irregularly distributed openings (Chamilothori, Chinazzo, et al., 2019; Chamilothori et al., 2016), as well as the work of Abboushi et al. (2019) where patterns of medium to high complexity were evaluated as more visually interesting. However, in the present study, façade variations that did not differ between them in perceived complexity differed in ratings of interest and pleasantness, and thus indicate the need for further work in identifying the characteristics of the façade composition driving these effects.

A significant effect of country, as well as a significant interaction between façade geometry and country, were found for ratings of excitement. In particular, Patterns 1, 2, and 3 led to higher evaluations of excitement in Greece compared to Switzerland. Pairwise comparisons showed that Pattern 3, in particular, was perceived as less exciting than Patterns 5 and 6 in Switzerland, but did not differ from them in Greece. This finding might be attributed to different associations towards these façade geometry variations in the two countries and merits further investigation.

When comparing Pattern 2 and 3 (straight and skewed vertical façade elements, respectively), findings showed significant differences in how pleasant, interesting, exciting, calming, and complex the same space was perceived, demonstrating a defining difference between these seemingly similar façade geometry variations. This simple shift of predominantly vertical elements from straight to slightly skewed resulted in a significant increase in the perceived pleasantness, interest, excitement, and calmness of the space, with a maximum estimated increase of up to 10% in the case of perceived interest. In other words, findings revealed that this design feature could induce consistently positive perceptual responses.

Regarding pleasantness, Patterns 3 and 6 led to the highest ratings, while they did not differ significantly between them. This finding is not reflected in ratings of complexity, where these two patterns differed (with Pattern 3 and 6 corresponding to a moderate and high level of complexity, respectively), and could be explained by the naturalness of the composition, which is related to preference in architectural interiors (Coburn et al., 2019).

Pattern 4, a design with irregularly distributed rectangular openings, led to a significant decrease in the perceived spaciousness, brightness, and satisfaction with the amount of view in the space. As all façade variations had the same perforation ratio, and the openings of Patterns 3, 5, and 6 were also irregularly distributed, this perceptual effect can be considered a result of the shape and the size of the openings. Although recent work by Konstantzos et al. (2015) has greatly contributed to our understanding of view clarity through fabrics, little is known regarding the view-related effects of the shape and size of openings of a shading system. The results of our study suggest that the fragmented view through Pattern 4 (compared to the continuous access to view out through Patterns 1, 2, and 3) or the existence of larger openings in Patterns 5 and 6 may have contributed to generating dissatisfaction with the amount of view to the outside, which, as expected, influenced in turn the perception of brightness and spaciousness in the scene. It would be of interest to examine further the effect of opening size and shape, which contribute to view clarity, as well as the content of the view on the satisfaction with the amount of view, as both factors are important for view quality (Ko, Kent, Schiavon, Levitt, & Betti, 2021).

4.3. Limitations and future research

The current study is, to our knowledge, the first to systematically investigate the perceptual and physiological effects of a wide range of façade variations that are inspired by existing buildings and differ solely in the shape and spatial distribution of their openings. Although the outcomes of this study bring important insights into the influence of façade geometry on spatial experience, they are still limited by the
methodological approach used in this study. Although the similarity between the experience of daylit scenes in real and VR environments is demonstrated in the literature (Abd-Alhamid et al., 2019; Chamilothori, Wienold, & Andersen, 2019), the use of VR limits both the realism and the luminaire range of the visual stimulus. As it is not possible to induce visual discomfort in the immersive scenes, the presented stimuli were always evaluated in comfortable visual conditions, which might not correspond to an equivalent real situation. Additional studies in real environments are necessary to address this shortcoming.

Moreover, it is important to point out demographic differences between the two samples. Even though all participants adhered to the minimum of 18 months of stay in the country of study for satisfactory adjustment, the percentage of participants whose country of origin was the same as the country of study was lower in Switzerland (30%) compared to Greece (94%), which might be explained by the fact that experiments were conducted in university campuses with different populations of foreign nationals. In addition, the percentage of participants reporting being trained in the area of architecture was higher in Greece (35%) than in Switzerland (8%), which could perhaps explain the interaction between façade geometry and country for ratings of excitement and warrants further investigation. These differences could potentially influence the results of the present study, and future research is invited to recruit more homogenous samples. Lastly, it is worth noting that the eligibility criteria for participation of normal or corrected-to-normal vision were confirmed verbally by the participants, rather than through explicit testing for vision deficiencies.

Regarding exposure to the presented scenes, a minimum exposure of 30 s was ensured for all presented stimuli, and the remaining exposure time was dictated by the participants, and lasted a few minutes at most (with an exposure time of \( M = 137.4 \) s, \( SD = 53.3 \) s in Greece and \( M = 124.9 \) s, \( SD = 38.6 \) s in Switzerland). Further research is needed to examine situations with longer exposure times, which can be difficult in virtual environments. This limitation is particularly relevant for findings on visual interest, which is linked to novelty (Silvia, 2008), an attribute that is expected to diminish with prolonged exposure time. Novelty is also related to the stimulus itself: while the horizontal and vertical stripes in the studied stimuli were chosen specifically due to the prevalence of visually similar façade systems in existing buildings, all other studied façade geometry variations are still a rare (although increasingly less so) occurrence. As such, the effects of façade geometry relating to impressions of interest and excitement in the present study might be driven not only by the geometric characteristics of the façade but also by the lack of familiarity with a particular design.

Due to current technical limitations, the immersive environments used in this study do not allow free movement and interaction with the scene, which could increase the participants’ sense of presence. Regarding the experimental design, even though the use of façade geometry as a within-subjects factor eliminates the inter-subject variance for that factor, it simultaneously places the focus of the participant on the sole changing feature of the scene. Although LMM analyses were used to explicitly account for the use of repeated measures, this experimental design introduces a possible stimulus range bias which might have contributed to the lack of a significant influence of sky type and spatial context on most subjective responses. Future studies are encouraged to employ experimental designs with sky type as a within-subjects factor to examine further the relative effect of sky type and façade geometry.

The present study found limited effects on physiological responses, which is generally expected as depictions of inanimate objects elicit low arousal (Dan-Glauser & Scherer, 2011). The higher decrease of skin conductance level (logΔSCL) compared to the baseline condition under exposure to scenes with large sun patches in the field of view and social context compared to overcast sky conditions in the working context indicates lower activation of the sympathetic nervous system. To bring more clarity to the potential effects of façade and light patterns on autonomic nervous system activation and stress recovery, a dedicated task for stress induction and longer exposure to the stimuli would be recommended.

Furthermore, a fixed viewing distance was used in all presented stimuli. Even studies have shown that the visual interest and preference of projected light patterns were not be affected by viewing distance (Abboushi et al., 2019), it is a factor that could affect the effects of façade geometry, particularly regarding satisfaction with the amount of view. Moreover, the two studied conditions of spatial context were differentiated only by the type of furniture placed in the scene. Although this approach is an improvement compared to the verbal instructions (without a change in the visual stimulus) that have been employed in the literature, the experimental manipulation could be even stronger (e.g., with richer content, or people interacting with the furniture). Future work could address this limitation through experiments where participants can perform different activities, which could also allow for examining possible conflicts between visual attention to the background and the task in the case of façade variations of high visual interest.

Lastly, the methodological approach of keeping a number of factors constant in the studied façade variations (such as the perforation ratio, depth, and material of the façade) leads to unavoidable limitations in the generalizability of the research findings to other façade designs. For example, the thickness of the façade, which in the present study was set to 1 cm, can affect the amount of view depending on the viewing angle, and could thus lead to different outcomes. Similarly, the reflectance of the façade materials could influence the perceived brightness of the space. Although these limitations do not diminish the relevance of the present findings, they motivate further work to examine additional façade characteristics and broaden our knowledge of the influence of façade design on occupants.

5. Conclusion

This article presents a VR-based experimental study where 256 participants were immersed in daylit interior scenes with varying façade geometry, sky type, and spatial context. The study was conducted in Switzerland and in Greece to investigate possible regional differences. Participants were asked to rate both their affective appraisal (how pleasant, interesting, exciting, and calming the space was perceived) and scalable attributes (how complex, bright, and spacious they found the scene and their level of satisfaction with the amount of view), and physiological responses (logΔSCL, ΔSCR, ΔRMSSD, ΔHR) were measured throughout their exposure to the VR scenes. Façade geometry significantly influenced the participants’ evaluations of all subjective attributes, while the sky type and the spatial context did not show a significant effect. Findings showed a significant effect of country and an interaction between country and façade geometry for perceived excitement, with participants in Greece rating specific façade variations as more exciting than participants in Switzerland. Analysis of skin conductance showed a significant effect of sky type, context, and their interaction only for the logΔSCL. The social context in a clear sky with low sun angle (and thus with large sun patches on the floor) led to a decrease in logΔSCL compared to the working context in overcast sky conditions, showing lower activation of the sympathetic nervous system and indicating that this condition was potentially less stressful, or less cognitively or attentionally demanding. No significant effects were found for either ΔSCR, ΔRMSSD, or ΔHR.

The findings of this study reveal that the façade geometry is the predominant factor, among those studied, influencing spatial experience. In addition, further analysis revealed consistent similarities in how certain façade variations were perceived, as well as façade variations that differed from all others regarding the responses they induced.

The outcomes of this study provide strong evidence for the
importance of the façade design not only as a crucial factor in the building energy consumption and the comfort of occupants, but also as a driver of the occupants’ experience of the space. In one of the most striking outcomes, the change of façade geometry from straight to slightly skewed vertical elements led to the same space being perceived as significantly more pleasant, interesting, exciting, and calming. Similarly, the façade geometry influenced scalable attributes, such as the reported brightness, spaciousness, and satisfaction with the amount of view in the scene. Although limited to short exposure in a VR context, these findings demonstrate that simply changing the design of façade openings may induce significant effects in our experience, and outline a very promising area for both research and practice in architecture, lighting, and environmental psychology.

Declaration of interest

The authors declare no conflicts of interest.

Author statement

Kynthia Chamilothori: Conceptualization; Methodology; Investigation; Formal analysis; Visualization; Funding acquisition; Writing - original draft; Writing - review & editing.

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Appendix A. Supplementary data

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