

Original Research Article

Geometric Patterns of Daylight Distribution and Sensory Perceptions of Residents in Residential Buildings*

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Abstract

Problem statement: Daylight is inherently dynamic and variable, which, depending on the architectural design characteristics of light-transmitting surfaces, especially their geometry, can create different patterns of light and shadow within the interior space. This, in turn, can affect the senses and sensory perceptions of residents, manifesting through their emotional responses and providing a distinctive and meaningful spatial experience. However, it appears that contemporary residential buildings do not provide an optimal level of perceptual effects of daylight in interior spaces for their residents. This may be due to architects' lack of systematic, clear, and precise awareness of the perceptual effects of daylight.

Research objective: This study aims to explain the relationship between geometric patterns of daylight distribution and the sensory perceptions of residents, as well as to identify the most reliable numerical indices for image processing to predict the relationship between these two aspects within the context of residential buildings.

Research method: This study has been conducted using a survey research method and an image processing method in a simulated environment.

Conclusion: The survey findings indicate that changes in the geometric patterns of daylight distribution significantly alter the average sensory perception assessment indices. This highlights the importance for architects to consider and manipulate the geometry of light-transmitting surfaces to create desirable environmental sensations. Additionally, the correlation findings between the survey research and the studied image processing indices suggest that the Michelson, mean-RMS, Fractal D, GIF file size, and RAW-PRIM⁸ indices are the most reliable for predicting pleasantness. The TIFF-SOBEL, JPEG-PERIM⁸, Michelson, JPEG file size, and PNG file size indices are the most reliable for predicting attractiveness. The TIFF-SOBEL, Mean mSC, JPEG-PERIM⁸, JPEG file size, and JPEG-PERIM⁴ indices are the most reliable for predicting excitement. The RAW-PRIM⁴, RAW-PRIM⁸, Michelson, Fractal D, and CANNY 2014-RAW indices are the most reliable for predicting spatial calmness.

Keywords: *Daylight, Sensory perceptions, Emotional responses, Simulated environment, Image processing indices.*

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Introduction

Daylight is inherently dynamic and variable. It can create contrasting and dynamic patterns of light and shadow, and varying brightness within an interior space, depending on the architectural design features of light-transmitting surfaces, particularly their geometry, as well as the building's geographical location, the time (hour, day, season), and weather conditions (clear or cloudy skies). This can influence the different sensory perceptions of the residents, manifested through their emotional reactions, creating a distinctive and meaningful spatial experience for individuals (Abboushi et al., 2019; Andersen, 2015, Chamilothori et al., 2019; Moscoso et al., 2020; Rockcastle et al., 2017c). Some architects and interior designers have been inclined towards this potential of daylight, and they strive to address not only the physical needs and quantitative variables of daylight but also the qualitative components and psychological needs of residents. These include the effects of daylight on the residents' senses and perceptions, the view and privacy in the interior space, and the aesthetic factors of the building's exterior. This approach has led them to use various geometric patterns in the design of light-transmitting surfaces, including double-skin or multi-layered facades and perforated shells. However, their evaluations seem to be generally personal, intuitive, or based on previous work experiences, and they lack systematic, clear, and precise awareness of the impacts of different geometric patterns of daylight distribution on the sensory perceptions of residents. Therefore, it seems that the optimal use of the inherent ability of daylight to enhance the mood of the interior space and the physical and mental health of the residents is linked to focusing on the design of light-transmitting surfaces through strategies derived from the results and findings of empirical research.

The research background indicates that although some researchers have explained the relationship between a limited number of different geometric patterns of daylight distribution and individuals' sensory perceptions (Abboushi et al., 2019; Chamilothori,

2019; Moscoso et al., 2020; Rockcastle et al., 2017a; Rockcastle et al., 2017b; Rockcastle et al., 2017c), there is a significant research gap in explaining the relationship between a wide range of geometric patterns of daylight distribution, in terms of shape and spatial distribution, and the resulting light patches on sensory perceptions, especially in the context of residential buildings. Additionally, since there are an unlimited number of geometric patterns of daylight distribution that can be applied to the light-transmitting surfaces of buildings and even slight changes in their geometry can create a significant difference in the type of spatial perception they generate, providing a comprehensive categorization and guidelines for architects to utilize the findings of these studies is challenging. Therefore, one of the best solutions to overcome this challenge is to utilize image processing sciences. This means that by explaining the relationship between the perceptual effects of some of these patterns and image processing indices, highly reliable results can be achieved, and these results can be generalized to a larger community (Amundadottir et al., 2017; Chamilothori, 2019; Rockcastle & Andersen, 2014; Rockcastle et al., 2017a., Rockcastle et al., 2017b; Rockcastle et al., 2017c). This research, using a survey method and image processing technique in a simulated environment, seeks to elucidate the relationship between "geometric patterns of daylight distribution" and "residents' sensory perceptions", as well as to identify and extract the most reliable "numerical image processing indices" for predicting the relationship between these two variables. Architects can evaluate, compare, and analyze the perceptual effects of daylight in their proposed designs by utilizing the findings of this research. Furthermore, by encouraging residents to utilize daylight more in interior spaces, architects can create a distinctive and meaningful spatial experience for them, ultimately promoting their mental well-being and quality of life. This underscores the importance of evidence-based design, where architectural design processes benefit from the results and findings of previous research.

Theoretical Foundations

• Sensory perceptions

In the field of environmental psychology, the process of human perception of the environment consists of three consecutive and interconnected steps: “human senses”, “sensory perception”, and “cognitive perception” (Fig. 1). Firstly, the “human senses” initiate any sensory reaction mediated by the human senses and the nervous system. In the next stage, “sensory perception”, information is selected and processed from sensory data, and in this step, the initial data are registered and categorized in the mind according to their characteristics; essentially, this stage involves mental imagery. The mental process involving evaluation, inference, and formation of mental concepts occurs in the final stage, namely “cognitive perception”. All three stages together contribute to the distinctiveness and meaningfulness of the environment for humans, leading to behavioral responses (Sarmadi et al., 2020).

Figs. 2 & 3 also explains the role and significance of sensory perceptions in the process of the relationship between humans and the environment, which ultimately leads to behavior, based on two theories: the conceptual framework of environmental responses by Nasar (2011) and the overall process of perception and cognition by Lang (2014).

As these two perspectives suggest, sensory perceptions manifest through individuals’ emotional or mental reactions and serve as an intermediary concept in the human-environment relationship. This means that sensory perceptions are influenced by environmental stimuli and affect the distinctiveness and meaningfulness of the environment for humans, ultimately impacting human behavior in the environment.

• Indices for evaluating sensory perceptions of daylight

The research background on the perceptual effects of daylight indicates that the impact of natural and artificial light on individuals’ sensory perceptions is measured by their emotional or mental reactions (Boubekri et al., 1991; Van Erp, 2008; Veitch, 2001). Researchers have consistently emphasized the importance of visual stimuli in evaluating different emotional responses of subjects (Ergan et al, 2018; Chamilothoni et al., 2019; Lang et al, 1993; lang, 1995; Leite et al., 2019; Zou and Ergan, 2019a; Zou and Ergan, 2019b).

As previously mentioned, the intermediate stage in the process of human perception of the environment is sensory perception, which is identified through various human sensations and manifested through individuals’ emotional reactions. Different perspectives (Fig. 4) have been presented for categorizing emotional responses in the fields of psychology and environmental psychology (Ekman & Davidson, 1994; Plutchik, 1980; Russell et al., 1981). According to the research background, Russell et al.’s (1981) circumplex model of affect has been the most reliable theory in studies related to assessing the relationship between geometric patterns of daylight distribution and individuals’ sensory perceptions (Abboushi et al., 2019; Boubekri, 1991; Chamilothoni et al., 2019).

Based on this model (Fig. 4), human emotional responses to the environment can be explained and illustrated in a two-dimensional circular space through two dimensions: pleasantness, which includes desirable orientations such as being exciting or relaxing, or undesirable ones such as being distressing or dull, and arousal, which reflects the intensity

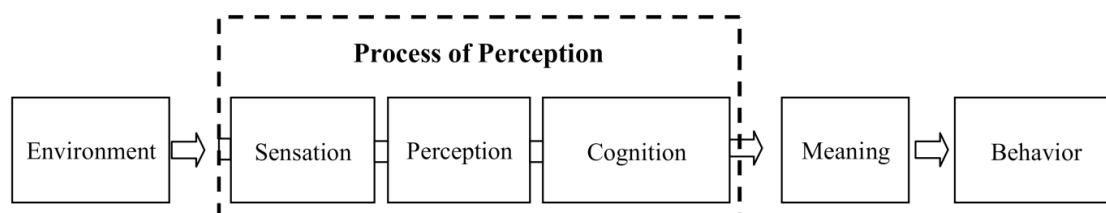


Fig. 1. The process of human sensations, perception, and cognition. Source: Sarmadi et al., 2020.

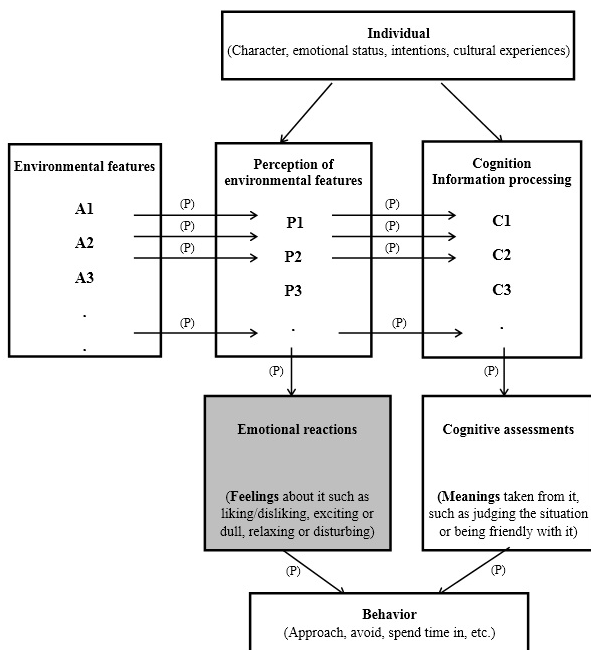


Fig. 2. Conceptual framework of environmental responses from Nasar's perspective. Source: Nasar, 2011.

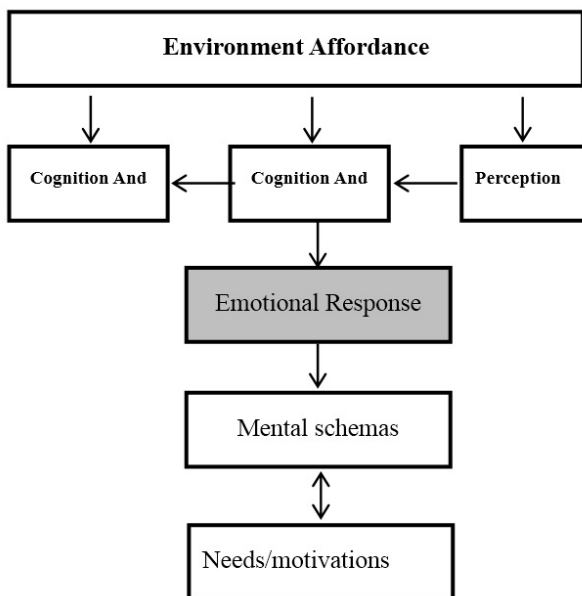


Fig. 3. Overall process of perception and cognition from Lang's perspective. Source: Lang, 2014.

of these feelings, such as the degree and intensity of excitement, relaxation, distress, or boredom experienced in the space. Vogels (2008) also states that coziness and liveliness in a space are elements that can reveal its ambiance, which appears to overlap and align with the dimensions of pleasantness and arousal described by Russell et al. (1981).

Another index mentioned in the research background

for evaluating individuals' emotional reactions to different daylight distribution conditions is the perception of space attractiveness (Abboushi et al., 2019; Boyce, 2014; Chamilothori et al., 2019; Rockcastle et al., 2017a). This criterion appears to align with the arousal dimension described by Russell et al. (1981) and the liveliness dimension proposed by Vogels (2008).

• Quantification and prediction of perceptual effects of daylight

According to research literature, one of the primary concerns of researchers is predicting the relationship between geometric patterns of daylight distribution and individuals' sensory perceptions through image processing methods and extracting image-based quantitative data (Amundadottir et al., 2017; Chamilothori, 2019; Rockcastle & Andersen, 2014; Rockcastle et al., 2017a; Rockcastle et al., 2017b; Rockcastle et al., 2017c). These studies assess the ability of various image-based criteria to predict participants' emotional responses to daylight distribution patterns; in other words, they determine the level of correlation between numerical image processing indices and participants' emotional reactions.

By quantifying the impact of daylight on residents' sensory perceptions of space and identifying and introducing reliable predictive indices, architects and designers will be able to evaluate, compare, and analyze the perceptual effects of their proposed designs during the design process, ultimately selecting the design that best addresses the design goals and issues at hand.

According to the research literature (Fig. 5), image processing quantitative indices include three indices for measuring contrast in space—mSC, MRS, and Michelson—and 22 indices for measuring spatial complexity. These complexity indices include image compression levels in formats such as GIF, JPEG, PNG, TIFF; edge detection indices RAW-PERIM8, RAW-CANNY2014, RAW-PERIM4, RAW-SOBEL, JPEG-, PNG-, TIFF-SOBEL, JPEG-, PNG-, TIFF-CANNY 2014, TIFF-PERIM4, JPEG-, PNG-, TIFF-

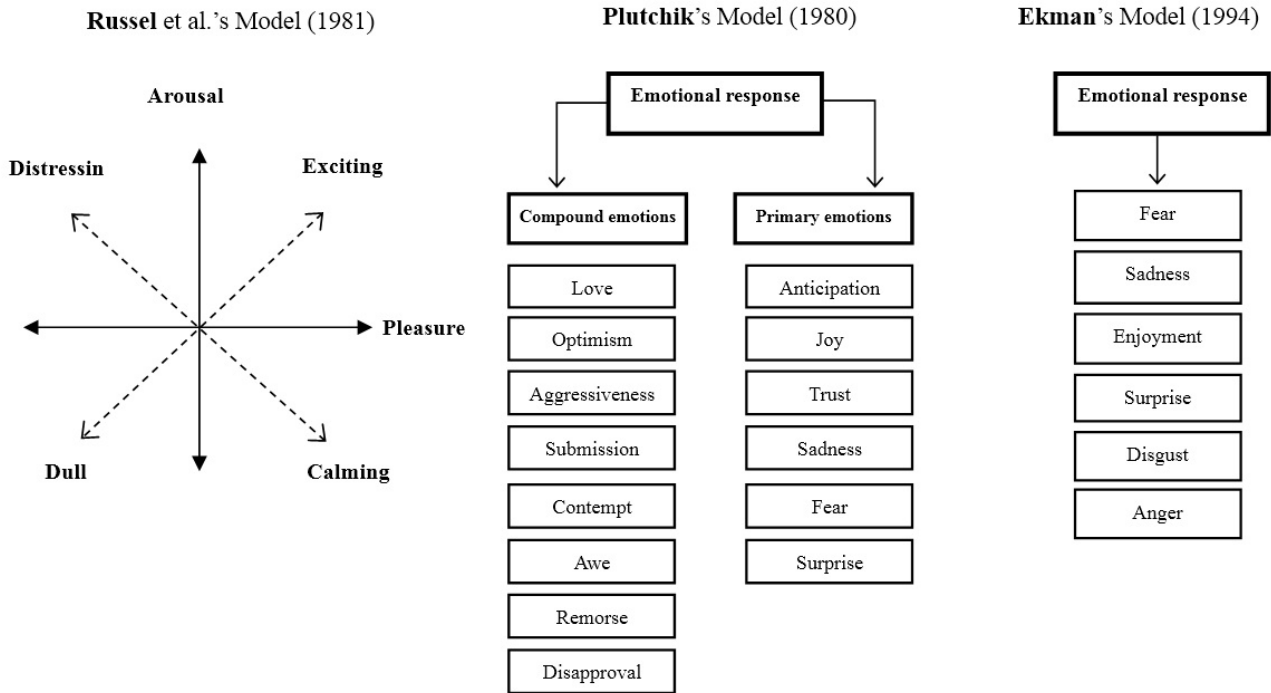


Fig. 4. Different Theoretical Perspectives on Categorizing Individuals' Emotional Responses in the Fields of Psychology and Environmental Psychology. Source: Authors.

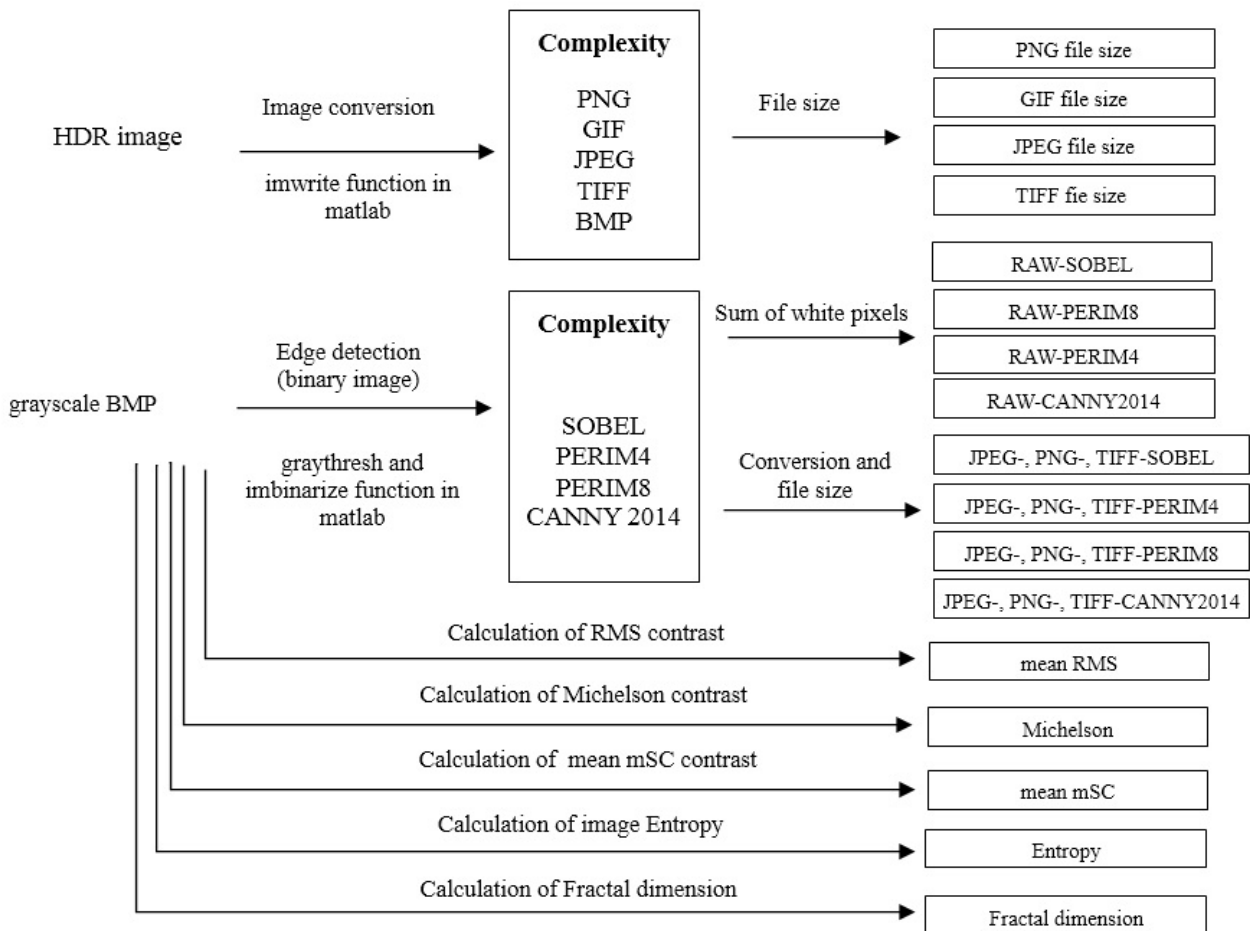


Fig. 5. An overview of the 25 numerical image processing indices studied in this research, derived from the research literature. Source: Rezaei & Sharghi, 2020.

PERIM8; and fractal dimension D and entropy indices derived from daylight-related research (Rezaei & Sharghi, 2020).

Research Methodology

This study is of an intra-subject or within-subject type; meaning that each participant experiences different distribution patterns in a simulated environment, and their self-reported data (survey method) is compared with their own responses. Through this comparison, the relationship between geometric patterns of daylight distribution and participants' sensory perceptions is evaluated. Additionally, to identify the most reliable image-based numerical indices for predicting the relationship between geometric patterns of daylight distribution and individuals' sensory perceptions, the findings from the survey research are compared with the findings from image processing research. Furthermore, the independent variables, dependent variables, control variables, research setting, participants, data collection methods and their validity, statistical methods for data analysis, and the quantitative image processing indices studied in this research are described and explained.

• Independent variables

The three linear geometries of horizontal lines, vertical lines, and grid geometry that are the most common types of geometries for residential building facades (especially exterior facades) and the research background also confirms their validity (Chamilothori, 2019) are included in the basic geometry and patterns (base shape) in this study. These three geometries are assumed to have the same depth (two-dimensional without depth), the same penetration level of 40% based on the background (Friedenberg & Liby, 2016), and the same frequency (13 spatial frequencies in the observer's field of view), and a consistent period (uniform spatial distribution; geometry formation with equal intervals) with the same materials in the case of a window, with the same length-to-width ratio (2.6 by 2.6 meters). In addition to these three basic geometries, 16 other geometries have been created by systematically

varying their spatial distribution (varying periods or intervals). These 16 geometries have a consistent 40% penetration rate (forming a uniform brightness surface) and a constant frequency of 13 spatial frequencies in the observer's field of view; however, they have systematically different spatial distributions (created with a 10% spectral reduction and increase in light penetration level), forming a spectral geometry (Fig. 6); thus, 19 different geometries of facade and direct sunlight penetration are simulated in the simulated environment, and under clear and uniform sky conditions, which are the independent variables of this study.

- Simulation

In this study, to establish the framework of the study area and simulate various patterns of daylight distribution, Rhino software was initially used to model 19 different geometries. All geometries measured in this study are placed in a hypothetical private sitting space, with a square window measuring 2.6 by 2.6 meters, and a square dimension of 4.20 by 4.40 meters with a height of 2.7 meters in the hypothetical viewing area on the first floor of a residential building in Tafresh County (Fig. 7). As shown in Fig. 7, after furnishing the sitting space, the position of the hypothetical observer (fixed position and viewing angle), perpendicular to the window axis, is determined at 4 meters from the window and 2.1 meters from the sides (middle of the space) and 1.21 meters above the floor, aligned with the observer's eye level. All space surfaces and furniture are colorless, and the window faces the geographical south. This space is furnished with a standard-sized three-seater sofa measuring 210 by 0.80 meters, a single-seater sofa measuring 0.90 by 0.80 meters, a coffee table measuring 1.20 by 0.80 meters (with a distance of 0.7 meters), curtains, and a potted plant. After modeling the 19 measured geometries (stimuli), all of them are rendered using the Diva plugin for the Rhino software based on the Physical-Based Rendering (PBR) rules, and final images are exported for the Radiance software. The study area in the Radiance software in Tafresh County, under

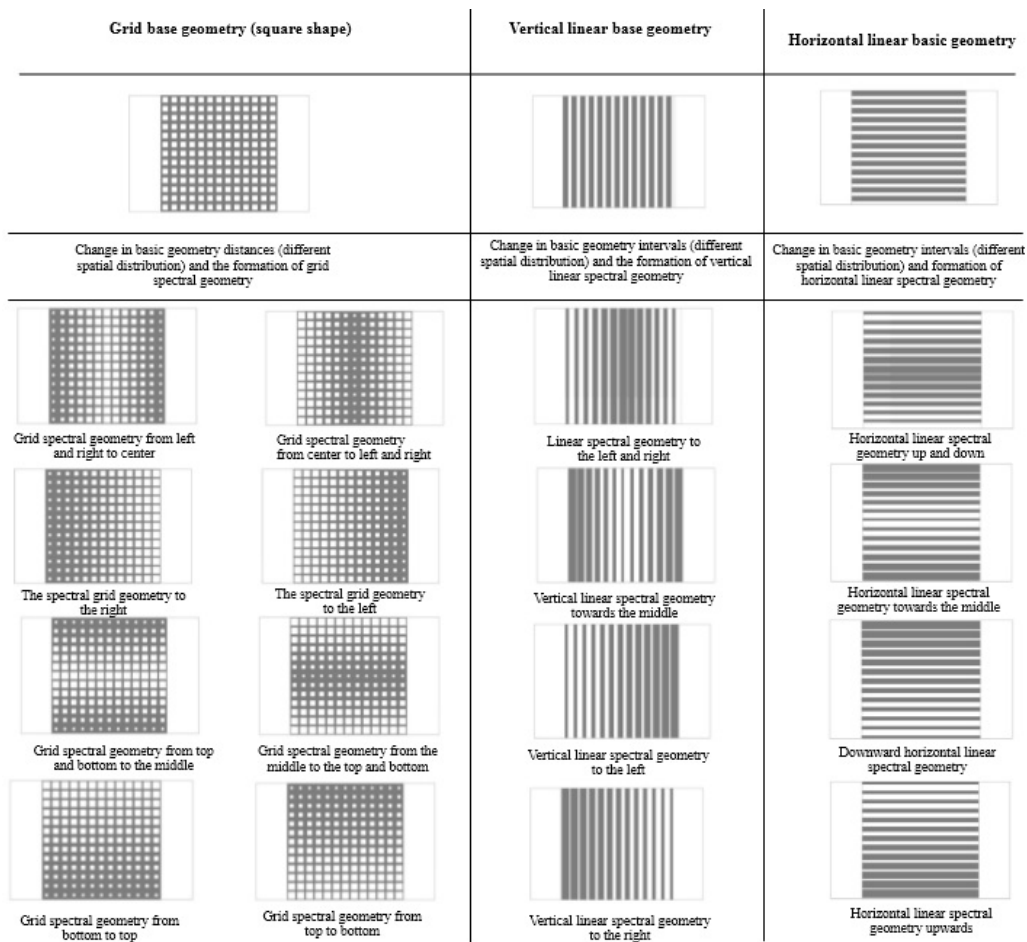


Fig. 6. Independent variables measured in this study: simple horizontal linear pattern and spectral horizontal linear pattern, simple vertical linear pattern and spectral vertical linear pattern, and grid and spectral grid (with a 10% spectral reduction and increase in light penetration) with a frequency of 13 spatial frequencies and a consistent 40% light penetration rate (consistent brightness level). Source: Authors.

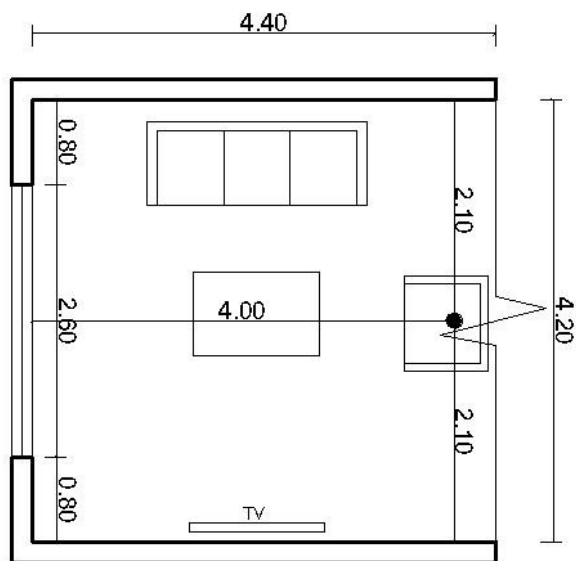


Fig. 7. Fixed position and viewing angle of the hypothetical observer in the study area. Source: Authors.

clear sky conditions, without external obstruction blocking light, without specific views or landscapes,

and November 28th, which according to research background (Rockcastle & Andersen, 2014) is one of the periods with the highest contrast of brightness and darkness indoors, is determined.

- Grouping of independent variables in the study

To reduce participant fatigue and prevent a sense of repetition and uniformity in the patterns of light distribution experienced by them, a maximum of six spaces are displayed instead of the original 19 spaces. For the categorization of independent variables, initially, the perspective of indoor spaces with high dynamic range (HDR) in the study area, as well as the position and viewing angle mentioned in the previous section, were expressed using Radiance software along with the characteristics of materials and variables specified in Table 1 & 2 with simulated medium-quality levels. Then, these images were converted to BMP or grayscale format. Furthermore,

Table 1. Characteristics of materials of the main surfaces in the study area in Radiance software. Source: Authors.

Surface	Material	B	G	R	Reflectance	Specularity	TVis
Ceiling	Plastic	0.8	0.8	0.8	80%	0	0
Floor	Plastic	0.4	0.4	0.4	40%	0	0
Wall	Plastic	0.7	0.7	0.7	70 %	0	0
Facade	Plastic	0.7	0.7	0.7	70 %	0	0
Furniture	Plastic	0.5	0.5	0.5	50%	0	0
Window	Glass	0.87	0.87	0.87	80 %	0	0.80

Table 2. (rpict) variables in Radiance software for simulating indoor perspective with medium-quality level. Source: Authors.

-ps	-pt	-pj	-dj	ds	-dt	-dc	-dr	-dp	-st	-ab	-aa	-ar	-ad	-as	-lr	-lw	-vv	-vh
2	0.5	0	0	0.15	0.5	0.75	3	512	0.15	5	0.1	512	4096	2048	8	0.005	60	80

the modified Spatial Contrast Index (mSC), identified as the most influential index for measuring brightness and darkness contrast according to previous research, was evaluated for the 19 proposed patterns in MATLAB software (2017b). Fig. 8 displays the ranking of perspectives of simulation patterns along with their brightness and darkness levels based on the modified spatial contrast index. Based on the measurement results of this index, the 19 patterns were equally and proportionally divided into three groups of six patterns each, meaning that in each group, there were two patterns with high contrast, two with medium contrast, and two with low contrast (Fig. 9). It is worth noting that the thirteenth grid pattern was excluded due to its proximity to the brightness and darkness contrast level (less than 0.2) with the fourteenth grid pattern.

- Displaying distribution patterns in the simulated environment

After categorizing the distribution patterns, final images with high dynamic range (HDR) and a fixed viewing angle of 80 degrees horizontally and 60 degrees vertically are simulated using Radiance software. These images, based on the characteristics of materials and specified variables in Tables 1 & 3, are simulated with a higher quality level than the previous section. After adjusting the monitor's and their brightness levels through tone mapping algorithms and conversion to grayscale images, they are presented to the participants.

• Dependent variable

As mentioned earlier, participants' sensory

perceptions (dependent variable) are measured through the assessment of their emotional reactions.

- Emotional reactions (Self-reported Data)

In this study, six simulated spaces are presented to participants from each group randomly. While individuals observe the simulated environment and imagine being present in the hypothetical private living room (Fig. 7) and engaging in discussions with family members and friends, they are verbally questioned about their level of pleasantness, visual attractiveness, emotional excitement, and calmness using an 11-point Likert scale (ranging from 0 to 10). The indicators of pleasantness, excitement, and calmness are derived from Russell et al., (1981) circumplex model of affect, and the visual attractiveness indicator is another measure derived from research related to the perceptual effects of daylight (Abboushi et al., 2019; Spehar et al, 2015; Van den Wymelenberg, 2012), which are influenced by different brightness conditions (darkness and brightness) of the space.

• Control variables

As previously mentioned, this study solely aims to assess the role of the geometry of daylight distribution patterns (shape and spatial distribution) on residents' sensory perceptions. Therefore, based on the research background, other variables that might influence this relationship are considered constant and neutral. These variables, as depicted in Table 4, include parameters related to daylight transmission, such as the dimensions of the aperture (floor-to-ceiling; 2.6 by 2.6 meters), light penetration rate (40 percent),

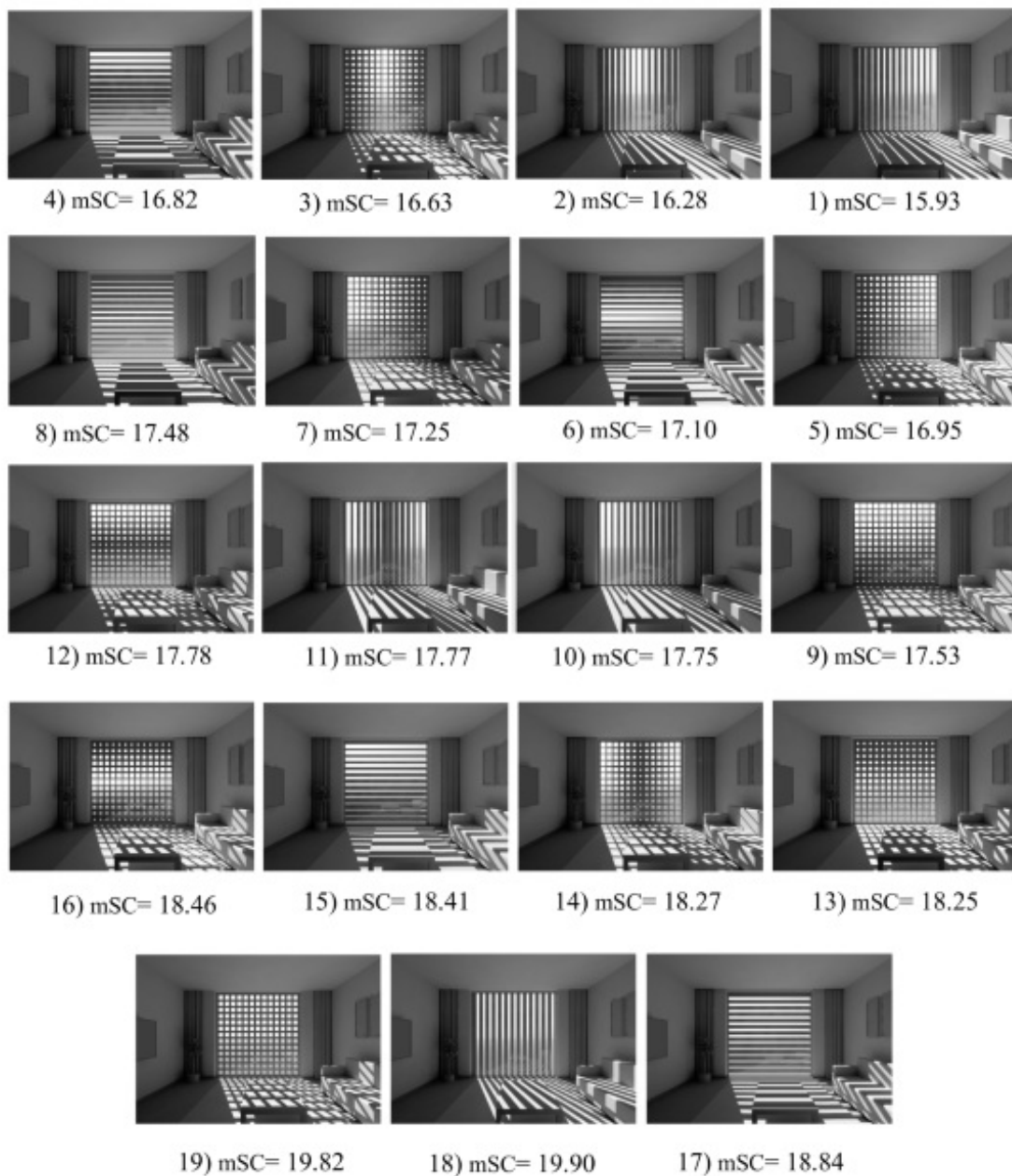


Fig. 8. Ranking of brightness and darkness levels of images using the modified Spatial Contrast Index (mSC). Source: Authors.

Table 3. (rpict) variables in Radiance software for simulating high-quality indoor perspective space. Source: Authors.

-ps	-pt	-pj	-dj	ds	-dt	-dc	-dr	-dp	-st	-ab	-aa	-ar	-ad	-as	-lr	-lw	-vv	-vh
1	0.5	0	0	0.15	0.5	0.75	3	512	0.05	5	0.05	512	20000	10000	8	0.002	60	80

materials (colorless), frequency of open and closed surfaces (13 spatial frequencies in the observer’s field of view), the depth of the window ledge (no depth, two-dimensional), window protrusion and recess, and shading (no window protrusion and recess, no shading). Additionally, factors related to the environment and surroundings are also considered,

such as space dimensions (length 4.4, width 4.2, height 2.6), furniture and surfaces (abstract and colorless), space activities (social interaction; imagining discussions with family members and friends in the private living space), building floor (first floor), view (without specific view or landscape), daylight obstructions (without specific obstruction), and in

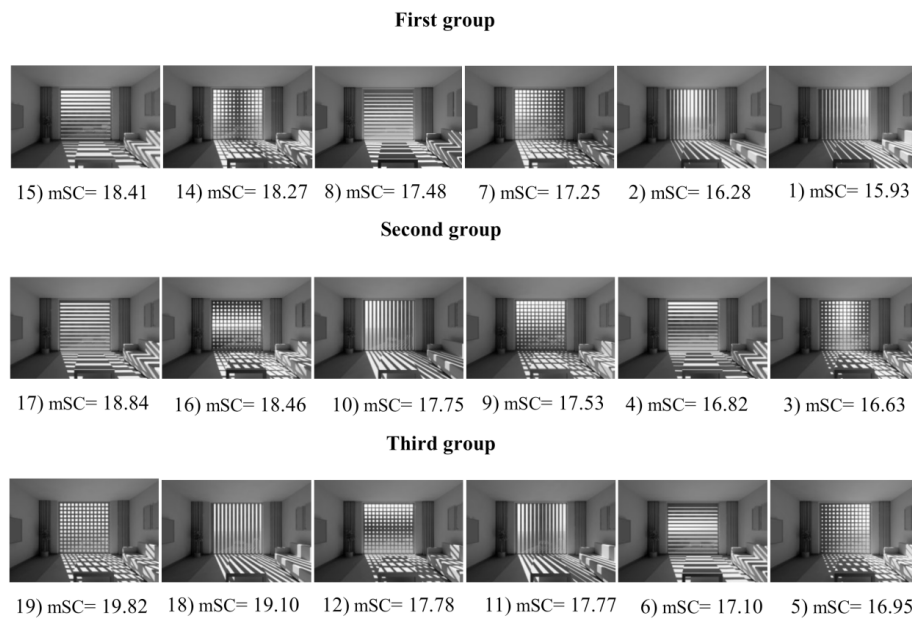


Fig. 9. Grouping of independent variables in the study based on the modified Spatial Contrast Index (mSC) into three groups of six, equally and proportionally. Source: Authors.

Table 4. A General Overview of Independent, Dependent, and Controlled Variables of the Study. Source: Authors.

Light Transmitting Facade (Facade)			
Variable	Type of Variable	Variable	Type of Variable
Orientation of Openings	Controlled (south side)	Spatial Distribution (Cycle Period)	Independent (10% spectral increase and decrease in light penetration level; Fig. 6)
Dimensions of Openings	Controlled (2.6 by 2.6 meters)	Frequency (Open and Closed surfaces)	Controlled (13 spatial frequencies in the viewer's angle of view)
Level of Light Penetration	Controlled (40%)	Depth	Controlled (without depth; two-dimensional)
Materials	Controlled (uniform; no color)	External Shading	Controlled (without external shading)
Shape	Independent (horizontal line, vertical line, grid)	Protrusion and Recession of Openings	Controlled (without protrusion and recession)
Study Context and Surrounding Environment			
Variable	Type of Variable	Variable	Type of Variable
Dimensions of Space	Controlled (length 44, width 42, height 26)	Building Floor	Controlled (first floor)
Furniture and Surfaces	Controlled, uniform (no color)	View and Landscape	Controlled (no specific landscape view)
Space Activities	Controlled (social interaction; discussion and chatting with family or friends in the residential living room)	Daylight Obstruction Barriers	Controlled (no obstruction)
Simulation			
Variable	Type of Variable	Variable	Type of Variable
Geographical Location	Controlled (Tafresh County)	Observer's Position and Viewing Angle	Controlled (uniform; Fig. 7)
Visible Light Transmission Coefficient of Glass	Controlled (88%)	Sky Conditions	Controlled (clear sky)
Observer's Eye Height	Controlled (sitting observer's eye height; 121 cm)	Time Section	Controlled (November 28th corresponding to December 7th at 11:10 AM)
Sensory Perceptions (Dependent Variable)			
Measurement through the emotional reactions of the participants (self-reported data) Includes: Sense of pleasure, sense of attractiveness, sense of excitement, and sense of calmness			

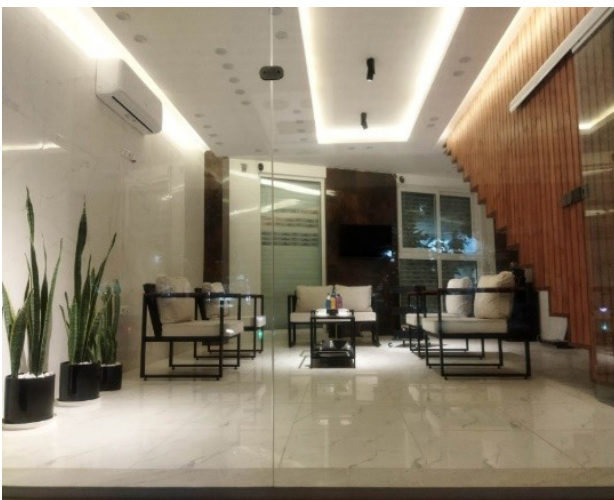


Fig. 10. Research setting and preparation conditions for the study after eliminating interfering environmental factors. Source: Authors.



Fig. 11. Research conditions and the method of displaying simulated images to the participants by systematically eliminating interfering environmental factors to increase their immersion in the simulated images. Source: Authors.

the simulation context, geographical location of the building (longitude and latitude of Tafresh County), visible light transmittance coefficient, observer's eye height (seated observer at 1.21 meters), observer's position and viewing angle (Fig. 7), sky conditions

(clear), and time frame (November 28th, coinciding with 7th of Azar, at 11:10 AM).

• Research setting

This study was conducted from April to August 2023 at the researcher's design office in Tafresh (Fig. 10). The reason for selecting Tafresh as the study location is due to its clean air and low-rise buildings, which result in minimal shadowing from adjacent buildings, thereby providing residents with a more pronounced and tangible experience of sunlight in residential buildings in this city. To display the simulated space, the brightness levels of HDR images (high-quality simulated images as specified in Table 3) were first matched with the brightness range of the display tool (a 43-inch Daewoo smart LED TV model DSI-43s7100EM) using tone mapping algorithms. Then, as shown in Fig. 10, these images were presented to the subjects. Additionally, as illustrated in Fig. 11, to enhance the subjects' immersion in the simulated space, environmental factors that could interfere with the research setting were systematically eliminated during image display, and both artificial and natural lighting in the environment were minimized.

• Participants

The participants of this study included 120 women and 120 men, aged 20 to 50, with optimal vision, residing in Tafresh. They were randomly and conveniently selected and randomly categorized into three groups of 80. The selection of non-expert subjects, the balance between the number of male and female subjects, and the age range were derived from the findings of previous studies (Chamilothori et al., 2019).

• Data collection method and validity

In this research, initial verbal explanations about the definitions of the emotional indices studied were provided to the participants. After verbally asking the subjects their age and gender, each was randomly shown a set of six simulated spaces in a random order. To explain the simulated residential setting being studied, it was stated after displaying the first space, "As is evident from the furnishings of the presented space, this environment is the private living room of

a residential house; imagine that you are present in it, sitting on a sofa, and chatting with family members or friends. Please keep this in mind when answering the questions verbally”. Before displaying each space, a monochromatic image based on the average RGB values of the six simulated images in each group was shown to the subjects to ensure color compatibility. They were then asked to remain silent for 30 seconds and focus on observing the simulated environment. After this period, the researcher informed the subjects, and upon their readiness, they were verbally questioned about the subjective indices being studied, and their responses were written and recorded on a prepared checklist.

• **Statistical methods for data analysis**

In this research, one-way ANOVA (analysis of variance) is used to compare the means and the impact of each pattern on the evaluated subjective indices. To assess the reliability of the 25 proposed image processing indices (Fig. 5) in predicting the perceptual effects of daylight, the Kullback-Leibler divergence method is utilized. This test determines the difference between the two probability distributions of subjective indices (pleasantness, attractiveness, excitement, and calmness) for daylight perception measurements in the survey research section, involving 240 participants and 25 image processing indices. If the result of this test is closer to zero, the difference between the two distributions is smaller, and vice versa. A value close to zero for the Kullback-Leibler divergence indicates that similar behavior can be expected from the two distributions, whereas a value close to one indicates that the two distributions exhibit opposing behaviors (Kullback & Leibler, 1951).

All statistical analyses in this research are conducted using MATLAB version 2017.

• **Quantitative image processing indices**

As mentioned in the theoretical foundations of the research (Fig. 5), the quantitative image indices studied in this research include three criteria for evaluating the contrast of light and dark spaces (mSC, MRS, and Michelson) and 22 indices for measuring spatial complexity, including image compression levels in GIF, JPEG, PNG, and TIFF formats; edge detection indices such as RAW-PERIM8, RAW-PERIM4, RAW-SOBEL, JPEG-, PNG-, TIFF-SOBEL, JPEG-, PNG-, TIFF-CANNY2014, JPEG-, PNG-, TIFF-PERIM4, JPEG-, PNG-, TIFF-PERIM8; and fractal dimension D and entropy, based on related daylight studies. At this stage, the simulated images from section 3-1-3, with a resolution of 1480 x 1024 and a total of 1,523,712 pixels, are used to measure the proposed indices for the 18 studied spaces in MATLAB (2017b).

Findings

• **Findings of One-Way ANOVA for Six Patterns from the First Group**

The results of the one-way ANOVA for six patterns from the first group (Fig. 12) regarding the pleasantness of the space show that the first pattern creates significantly more pleasantness in the space compared to the fourth pattern (F:3.8, Sig:0.04), and the sixth pattern compared to the second pattern (F:3.3, Sig:0.008). Regarding the attractiveness of the space, the third pattern creates significantly more attractiveness compared to the first pattern (F:4.2, Sig:0.05). In terms of excitement, the third pattern generates significantly more excitement compared to the first pattern (F:5.8, Sig:0.04). Additionally, for the sense of calmness, the sixth pattern provides significantly more calmness in the space compared to the fifth pattern (F:5.9, Sig:0.03).

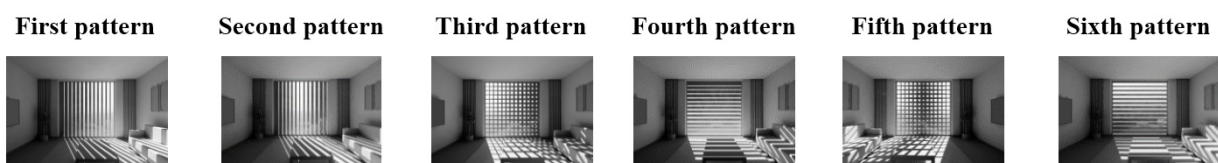


Fig. 12. Six patterns from the first group studied. Source: Authors.

• **Findings of One-Way ANOVA for Six Patterns from the second group**

Regarding the sense of pleasantness in the space (Fig. 13), the results show that the first pattern significantly creates more pleasantness compared to the fourth pattern (F:3.8, Sig:0.03), the first pattern compared to the sixth pattern (F:5.1, Sig:0.04), the fifth pattern compared to the fourth pattern (F:7.1, Sig:0.007), and the fifth pattern compared to the sixth pattern (F:4.6, Sig:0.03). In terms of the sense of attractiveness in the space, the first pattern significantly creates more attractiveness compared to the fourth pattern (F:6.4, Sig:0.02), the fourth pattern compared to the fifth pattern (F:5.1, Sig:0.02), and the fifth pattern compared to the sixth pattern (F:6.6, Sig:0.03). For the sense of excitement, the third pattern significantly creates more excitement in the space compared to the second pattern (F:7.1, Sig:0.04). Regarding the sense of calmness, the fifth pattern significantly creates more calmness in the space compared to the third pattern (F:6.7, Sig:0.05).

• **Findings of one-way ANOVA for six patterns from the third group**

Regarding the sense of pleasantness in the space (Fig. 14), the results show that the first pattern significantly creates more pleasantness compared to the fifth pattern (F:4.1, Sig:0.05), the second pattern compared to the third pattern (F:6.3, Sig:0.02), and the second pattern

compared to the fifth pattern (F:8.1, Sig:0.03). In terms of the sense of attractiveness in the space, the first pattern significantly creates more attractiveness compared to the sixth pattern (F:4.1, Sig:0.05), the second pattern compared to the third pattern (F:6.3, Sig:0.02), and the second pattern compared to the fifth pattern (F:8.1, Sig:0.03). For the sense of excitement, the first pattern significantly creates more excitement compared to the fifth pattern (F:6.3, Sig:0.03) and the fourth pattern compared to the fifth pattern (F:6.3, Sig:0.01). Regarding the sense of calmness, the second pattern significantly creates more calmness in the space compared to the fifth pattern (F:6.8, Sig:0.03).

Fig. 15 shows the coordinates of each pattern from the first, second, and third groups in comparison to each other based on the circular model of emotional responses by Russell et al. (1981).

- **Comparison of Findings on the Complexity Level Indicators of Simulated Images with Emotional Reactions of Spatial Pleasantness**

The comparison indicates that the relationship between the complexity level of simulated spaces and the feeling of pleasantness follows an inverted U-shaped curve. This means that daylight distribution patterns with moderate complexity levels elicit higher pleasantness compared to those with low or high complexity levels. Table 5 shows the results of the Kullback-Leibler divergence test for each indicator of pleasantness,

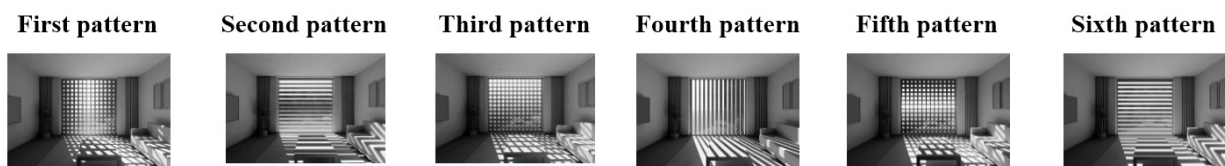


Fig. 13. Six patterns from the second group studied. Source: Authors.

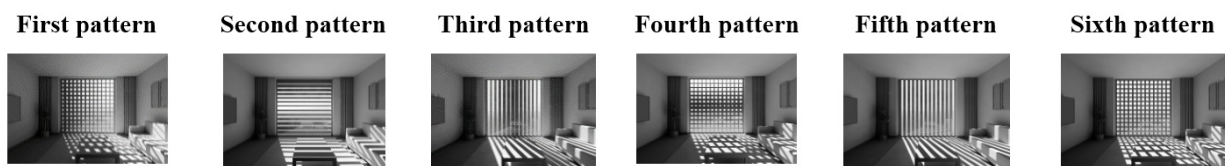


Fig. 14. Six patterns from the third group studied. Source: Authors.

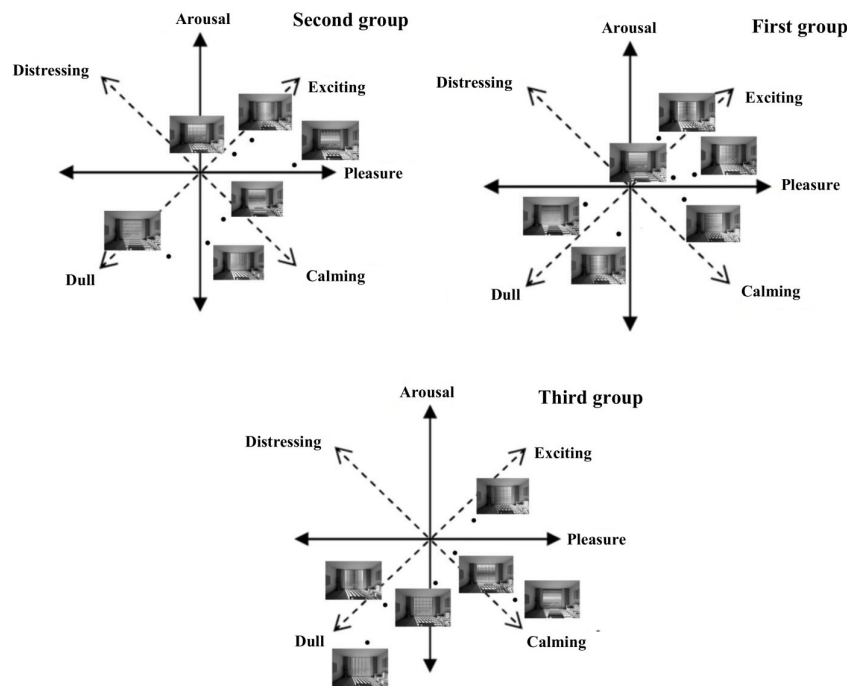


Fig. 15. The coordinates of each pattern from the first, second, and third groups in comparison to each other, based on the circular model of emotional perceptions by Russell et al. (1981). Source: Authors.

attractiveness, excitement, and calmness, along with 25 image processing indices, based on the normal distribution of the frequency of positive responses (5 and above) from 240 participants, arranged from the first to the eighteenth pattern studied. The top five priorities of each image-based index in predicting each subjective indicator of sensory perceptions are marked with superscript numbers from 1 to 5.

As shown in [Table 5](#):

- The indices Michelson, mean-RMS, Fractal D, GIF file size, and RAW-PRIM 8 are the most reliable in predicting the feeling of pleasantness in a space.
- The indices TIFF-SOBEL, JPEG-PERIM8, Michelson, JPEG file size, and PNG file size are the most reliable in predicting the feeling of attractiveness in a space.
- The indices TIFF-SOBEL, Mean mSC, JPEG-PERIM8, JPEG file size, and JPEG-PERIM 4 are the most reliable in predicting the feeling of excitement in a space.
- The indices RAW-PRIM4, RAW-PRIM8, Michelson, Fractal D, and RAW-CANNY 2014 are the most reliable in predicting the feeling of calmness in a space.

Conclusion

Daylight has a dynamic and variable nature that, depending on the architectural design of light-transmitting facades, particularly their geometry, can create different dark and bright spots in the interior space. This affects the senses and sensory perceptions of the occupants, which are manifested through their emotional reactions, thus providing a unique and meaningful spatial experience for individuals. This research, using a survey method and 25 image processing techniques in a simulated environment, seeks to explain the relationship between “geometric patterns of daylight distribution” and “sensory perceptions” of occupants in residential buildings and to identify the most reliable “quantitative image processing indicators” for predicting the relationship between the two. For this purpose, sensory perceptions were measured through emotional reactions of pleasantness, attractiveness, excitement, and calmness in the space. The geometric patterns of daylight distribution were evaluated based on three basic geometries: horizontal linear, vertical linear, and grid geometry, along with 15 geometries derived from these three basic geometries, featuring

Table 5. Findings from the Kullback-Leibler divergence test for each indicator of pleasantness, attractiveness, excitement, and calmness, and 25 image processing indices (the priority of each image-based index in predicting each subjective indicator is marked with superscript numbers from 1 to 5). Source: Authors.

	Metrics	Pleasant	Interesting	Exciting	Calming
File conversion metrics	PNG file size	0.028	0.034 ⁵	0.075	0.045
	GIF file size	0.018 ⁴	0.038	0.042	0.053
	JPEG file size	0.030	0.023 ⁴	0.025 ⁴	0.057
	TIFF file size	0.038	0.045	0.059	0.182
Edge detection metrics (sum of white pixels)	RAW-SOBEL	0.092	0.036	0.032	0.156
	RAW-PRIM4	0.031	0.079	0.094	0.010 ¹
	RAW-PRIM8	0.025 ⁵	0.066	0.073	0.013 ²
	RAW-CANNY2014	0.027	0.038	0.050	0.029 ⁵
Edge detection metrics (conversion and file size)	JPEG-SOBEL	0.191	0.105	0.089	0.31
	PNG-SOBEL	0.156	0.073	0.065	0.260
	TIFF-SOBEL	0.042	0.008 ¹	0.006 ¹	0.097
	PERIM4- JPEG	0.034	0.038	0.027 ⁵	0.078
	PERIM4- PNG	0.170	0.074	0.117	0.235
	TIFF-PRIM4	0.071	0.098	0.114	0.086
	JPEG -PERIM8	0.036	0.016 ²	0.021 ³	0.076
	PNG- PERIM8	0.140	0.057	0.053	0.220
	TIFF-PRIM8	0.112	0.131	0.136	0.097
	JPEG-CANNY2014	0.059	0.155	0.174	0.078
	PNG-CANNY2014	0.250	0.420	0.453	0.170
	TIFF-CANNY2014	0.210	0.185	0.196	0.205
Contrast metrics	Mean-RMS	0.0163	0.041	0.058	0.143
	Michelson	0.009 ¹	0.018 ³	0.071	0.016 ³
	Mean mSC	0.061	0.084	0.014 ²	0.108
Complexity metrics	Entropy	0.027	0.055	0.146	0.063
	Fractal D	0.013 ²	0.059	0.067	0.027 ⁴

systematic and varied spatial distribution including a spectral increase and decrease of 10% in light penetration, creating a spectrum-like geometry. The findings from the survey in the simulated environment show that the mean values of some of the evaluated subjective indicators significantly change with variations in the geometric patterns of daylight distribution. This highlights the importance for architects and designers to consider and manipulate the geometry of light-transmitting facades to create desired environmental feelings or sets of feelings. Another key finding is the inverted U-shaped relationship between the complexity level of simulated spaces and the feeling of pleasantness. Specifically, daylight distribution patterns with moderate complexity levels generate higher feelings of pleasantness compared to those with

low or high complexity levels. This finding aligns with previous research (Abboushi et al., 2019; Chamilothori, 2019; Friedenber and Liby, 2016) and validates these results.

The findings connecting the survey research with image processing research indicate that the Michelson, mean-RMS, Fractal D, GIF file size, and RAW-PRIM 8 indices are the most reliable in predicting the feeling of pleasantness in a space. The TIFF-SOBEL, JPEG-PERIM8, Michelson, JPEG file size, and PNG file size indices are the most reliable in predicting the feeling of attractiveness in a space. The TIFF-SOBEL, Mean mSC, JPEG-PERIM8, JPEG file size, and JPEG-PERIM 4 indices are the most reliable in predicting the feeling of excitement in a space. The RAW-PRIM4, RAW-PRIM8, Michelson, Fractal D, and CANNY

2014 indices are the most reliable in predicting the feeling of calmness in a space. It is worth noting that the reliability of the mean mSC index in predicting the feeling of excitement in this study aligns with previous research results (Rockcastle, 2017; Chamilothori, 2019), emphasizing the high reliability and generalizability of this index in predicting the subjective feeling of excitement in a space.

Fig. 16 schematically illustrates the application of this research's results in predicting the relationship between "geometric patterns of daylight distribution" and the "sensory perceptions" of occupants, according to the circular model of sensory perceptions by Russell and colleagues. According to this chart, architects can simulate the geometric patterns of daylight distribution in their proposed designs based on the guidelines outlined in the research methodology section. They can then evaluate, compare, and analyze the proposed different geometric patterns by determining the values of reliable quantitative image processing indicators derived from the findings of this study. For this purpose, designers initially measure the indicators related to the pleasantness of the space, which determine the orientation of desirable or undesirable emotional reactions in each pattern. Then, by evaluating other indicators related to excitement and calmness, they assess whether their proposed patterns are exciting or

distressing, calming or dull. Therefore, the interpretation of the measurement of the reliable indicators is as follows:

- A pattern where the levels of indicators related to pleasantness and excitement are at their highest compared to other patterns is expected to create a more desirable and exciting atmosphere in the space compared to other patterns.
- A pattern where the level of indicators related to pleasantness is at its highest and the level of indicators related to calmness is lower than in other patterns is expected to create a more desirable calming atmosphere in the space compared to other patterns.
- A pattern where the level of indicators related to pleasantness is at its lowest and the level of indicators related to excitement is at its highest compared to other patterns is expected to create a more undesirable distressing atmosphere in the space compared to other patterns.
- A pattern where the level of indicators related to pleasantness is at its lowest and the level of indicators related to excitement is also at its lowest compared to other patterns is expected to create a more undesirable monotonous and dull atmosphere in the space compared to other patterns.

Predicting the perceptual effects of daylight requires conducting numerous future studies with different

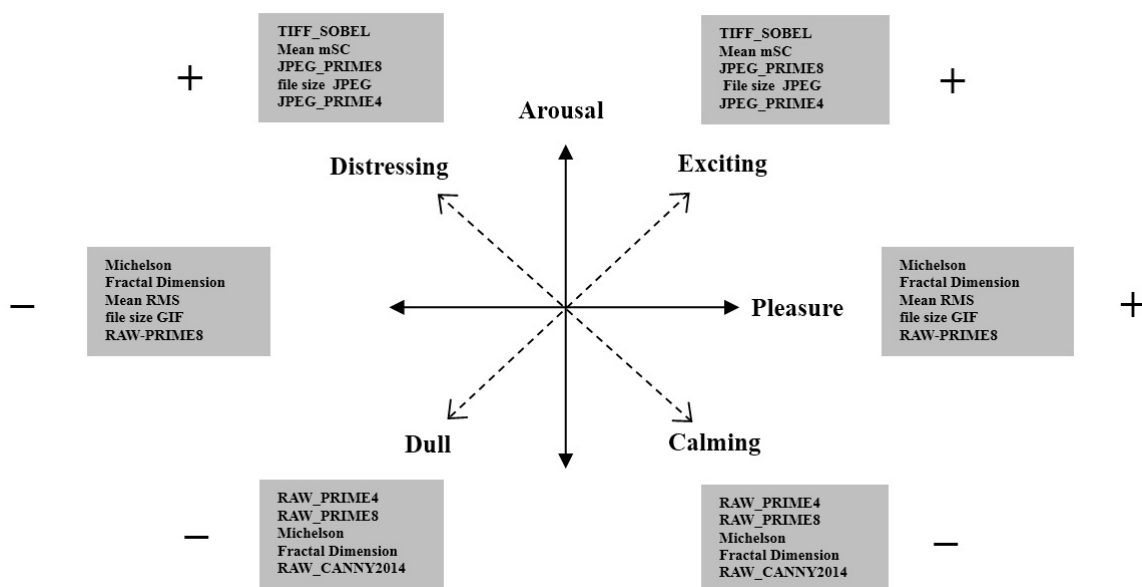


Fig. 16. Schematic application of this research's results in predicting the relationship between geometric patterns of daylight distribution and sensory perceptions of occupants based on the circular model of sensory perceptions by Russell and colleagues. Source: Authors.

geometric patterns of daylight distribution. By overlapping their findings, results with high reliability and generalizability can be achieved. It is recommended that future research, aiming for highly reliable and generalizable results, evaluate individuals' emotional responses simultaneously through three methods:

1. Survey method

2. Laboratory method includes:

-Measuring brain activity (Electroencephalogram sensors: EEG)

-Facial expression (Facial electromyography sensors: f-EMG) to assess both the pleasantness and arousal aspects

-Measuring heart rate (Photoplethysmogram sensor: PPG)

-Skin conductance (Galvanic Skin Response sensor: GSR) to evaluate attention level and arousal

3. Observational method include:

-Measuring head and eye movement (Eye-tracking and head-tracking sensors).

In summary, expanding research in this field will ultimately lead to one of the main achievements: developing software that architects and interior designers can use during the ideation and evaluation of proposed solutions and their development in the design process. This software would allow them to assess, compare, and analyze the perceptual effects of daylight in their proposed designs based on various factors, including the building's geographic location, time (hour, day, season), sky conditions (clear or cloudy), observer's position in the space, observer's viewing angle, observer's eye-level height, type of activities in the space, dimensions and area of the space, furniture and materials, and landscape. In the end, they would select the design that best responds to the design goals and issues at hand. This approach emphasizes evidence-based design, where architectural design processes utilize findings and outcomes from previous research.

Conflict of Interest

The authors declare that there is no conflict of interest in conducting this research.

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