Where Do We Look? An Eye-Tracking Study of Architectural Features in Building Design

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Abstract

Built environment plays an essential role in shaping the physical, physiological, and psychological human well-being given the fact that we spend more than ¾ of our times indoors. Various studies that investigated the impact of architecture on human health and well-being provided evidences on the influence of architecture with faster recovery in hospitals, better learning in schools, and more productivity in offices under variant configurations of architectural design features. This paper studied the impact of architectural design features (e.g., presence/size of windows, level of natural light and nature view) on human experience in buildings using a mobile eye-tracking solution to capture the subjects' attention toward various design features. The subjects were exposed to two distinct virtual environments designed with polarizing features, and were instructed to conduct a series of navigational and informational tasks. The eye-tracking results showed that subjects were more focused and had higher attention level in the positively configured virtual environment. The result of the informational task, where the subjects were asked to recall an array of words they just saw in the virtual environment, showed that subjects performed better (i.e., recalled more words) and experienced positive recall (i.e., recalled more positive words) in the positively configured environment.

Keywords

Eye-Tracking • Architectural design • Virtual reality • Human experience

52.1 Introduction

Architectural design could influence health and well-being of residents, since people spend most of their time inside of buildings [1]. Poorly designed buildings could cause physical and psychological discomfort for the occupants, such as Sick Building Syndrome (SBS), where the occupants experience sickness and discomfort that appear to be linked to the time spent in buildings [2]. As a result, fully understanding if certain architectural design features, such as (1) the presence of windows, (2) size of windows, (3) presence of natural light, and (4) presence of nature views, have any effects on human experience in buildings is a challenging task in architectural design. It is well known that these features could influence human emotions [3], hence impacting human health, well-being, and productivity [4, 5]. Previous studies on architectural design features' impact on humans mostly focused on surveying occupants after the construction is complete [6]. These survey studies were time-consuming and prone to errors introduced by the subjective feelings and demographics of the surveyed. As a result, there is still a need to objectively quantify the building design features' impact on human experience.

Previous research on quantifying the relationship between architectural design features and human emotions used Body Sensor Networks (BSN) as a data collection platform to record the subjects' physiological metrics (i.e., heart rate, facial

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muscle movement, and skin conductance) [7]. The results showed that environments with different architectural design features could cause statistical significant differences in BSN data [7]. However, the causal relationship of design features and human emotions is still inconclusive [8, 9].

As a result, it is essential to pinpoint the architectural design features that are causing the variance of human experience in architectural spaces, and eye-tracking technology is well suited for this purpose. Eye-trackers are devices that measure eye movement, which reflects the visual attention and gaze patterns of users [10]. Eye movement and gaze patterns have been related to attention and cognition, which are quantifiable links to the subjects' brain activities (e.g., scene awareness, perception of environment) [11, 12]. As a result, by measuring the visual stimuli and the subjects' eye movement, one could gain insights to the subjects' search patterns, attention, and most importantly, the causal relationship of the visual stimuli (i.e., the architectural design features) and the human emotions.

The objective of this paper is to study whether certain architectural features have any impact on human experience in buildings. Furthermore, this paper quantifies the extent of such impact by conducting user studies using a mobile eye-tracking solution, during which the participants were instructed to carry out tasks in distinctly configured virtual environments with various design features. Participants' responses were later analyzed and the implications of architectural features on human experience were discussed.

52.2 Background

52.2.1 Eye-Tracking Applications

Eye-tracking technology has been widely used in various areas of research, such as marketing, Human-Computer Interaction (HCI), safety simulation, and construction safety [10, 12–14]. A concise summary of the application areas of these research fields is presented in Table 52.1. Among these applications, the main purpose of using eye-tracking technology is to measure the attention of the users, hence inferring the users' situation awareness (i.e., safety simulation and construction safety), aesthetic preference (i.e., marketing), and viewing behavior (i.e., HCI). The experiment set-up used in the previous studies usually contain conducting interviews within a focus group while using eye-tracking technology to monitor the participants attention towards the Area of Interest (AOI), which is defined as the specific parts of a product or a design that is of interest to the researcher [15]. However, this kind of set up will not work for Architecture, Engineering and Construction (AEC) applications, since the workflow in AEC either requires onsite visits [10, 11] or immersive representation of a design model [16, 17].

In the Architectural Engineering and Construction (AEC) domain, eye-tracking has not received much recognition until the past decade due to some technological obstacles, such as the cumbersome size of eye-trackers, non-reliable eye-tracking outcomes, and hard to interpret results [15]. Accuracy (i.e., difference between actual gaze point and the measured point) and sampling frequency (i.e., average number of samples captured by eye-trackers) are the main specifications of eye-tracking technology. Low accuracy and low sampling rate used to be the roadblock for using eye-tracking technology in the AEC industry. However, with the fast technology development, eye-trackers nowadays are miniaturized to the size of a pair of glasses capable of accurate high rate sampling, and the development of eye-tracking data analyzing tools has made it possible for a larger number of AEC practitioners and researchers to utilize eye-tracking in their workflows. The most common use cases of eye-tracking in AEC include monitoring the construction workers' attention for construction safety awareness and conducting safety education for novice construction workers [10]. However, few studies focused on using eye-tracking for architectural design [1, 11]. One of the main reasons is that while designs can be rendered in a 2D or 3D

Table 52.1 Eye-tracking technology applications

Research area	Application
Marketing	• Web design [18] • Print advertisement [13]
Human-computer interaction (HCI)	• Brain-computer interface (BCI) [12] • Visual hierarchy and viewing behavior [19]
Safety simulation	• Flight simulator [14] • Driving simulator [20]
Construction safety	• Construction worker safety [11] • Construction safety education [10]

drawing, it is still challenging for people to experience the design features when they are only seeing a static drawing on a screen [16]. As a result, to achieve the measurement of the subjects' attention when experiencing various architectural designs, there is a need to create interactive virtual environments [7, 17].

52.2.2 Eye-Tracking Metrics

Fixations and saccades are the main metrics used when analyzing eye-tracking data [21]. A fixation is defined as a relatively motionless gaze on an AOI, whereas a saccade is defined as a quick eye movement that separates fixations [10]. Fixation and saccade each has a suite of related metrics that can be generated from eye-tracking data, such as fixation location/duration, saccade amplitudes/count. Fixation location indicates the person's attention, and fixation duration indicates the level of cognitive difficulty [1]. On the other hand, saccades only represent rapid eye movement, during which no visual information is stored or recognized [11]. As a result, only fixation related metrics are used in this study. A brief summary of those metrics is provided in Table 52.2.

52.3 Method

The authors conducted experiments with human subjects to monitor their attention while they were interacting with spaces configured with various design features. The total number of participants was 22, all of whom were graduate students from the department of civil and urban engineering. Hence, the subjects have adequate knowledge of architectural design.

To measure human responses towards different architectural features, two virtual environments with polarized features (marked as positive and negative) were developed in a game engine, by converting building information models to virtual environments [26]. The two virtual environments were identical, except for certain architectural features (see Table 52.3). On the one hand, the positive environment was designed with larger windows, ample natural light, and a view of green plants outside of the glass curtain walls. On the other hand, the negative environment was designed with smaller or no windows, only artificial lights, and closed concrete walls with no nature view. The design features included in the experiment are shown in Table 52.3.

22 participants were recruited to conduct the experiment and execute various tasks in the virtual environments. The tasks were separated into two categories, navigational and informational. For navigational tasks, the participants were directed to find specific objects located in certain rooms. For informational tasks, the participants were instructed to read an array of 10 words from an information panel, and then immediately write down the text they remember. It is hypothesized that the participants would show positive reactions (e.g., more focused, faster responses) in the positive environment, and vice versa. A widely adopted mobile eye-tracking solution was used during the user experiments to collect data about the participants' attention to the Area of Interests (AOI). The AOIs are defined as the video frames that contain different design features, while the subjects were conducting either navigational or informational tasks in those frames in two virtual environments. For example, in Fig. 52.1, the subjects were asked to go to the room at the end of the hall (navigational task). While they were walking towards the room, various design features, such as window size, natural light, and nature view were implemented in the corridor. And these features (i.e., presence of windows, window size, natural light, and nature view) are

Table 52.2 Eye-tracking metrics

Metric	Description
Area of interest (AOI)	Video frames containing design features (i.e., presence/size of windows, amount of natural light, presence of nature view)
Heat map	Distribution of the visual attention. (More hotspots indicate less focused attention) [22]
Number of fixations	Number of periods in which the eyes of a respondent are locked toward a specific object. (A large number of fixation indicates the task is complex and the subjects showed decreased efficiency in searching and navigating tasks) [23]
Time to first fixation	The amount of time it takes a respondent to look at a specific AOI. (Smaller TTFF indicates the high attention level and more focused mind) [24]
Time spent	The amount of time a respondent has spent on an AOI. (Less time spent means higher attention level) [25]

Table 52.3 Values in VEs for design features influential to human emotions

Architectural design features	Positive VE	Negative VE
Presence of windows	Has windows in measured corridors and rooms	No windows in measured corridors and rooms
Size of windows	Large size windows (60% Window to Wall Ratio)	Small windows (20% Window to Wall Ratio)
Amount of natural daylight	Sufficient amount of natural daylight (300 lx of luminance), brought in by windows in the measured room/corridor	Only artificial light and no window in the measured room/corridor
Exposure to nature view	Connection to external built environment and visible nature views	No connection to external built environment or visible nature views

Fig. 52.1 Polarized design features in positive (left) and negative (right) environments

defined as the AOIs. By looking into the eye-tracking metrics of these AOIs, the authors were able to gain insights of the subjects' attention towards the design features.

The experiment set up and flow are shown in Fig. 52.2. The virtual environments were shown on a 98-inch screen, and the user interaction was handled by an Apex device with a joystick for moving around and a button for triggering functions. The eye-tracking solution used was a mobile eye-tracking device in the form of a pair of glasses (as shown in Fig. 52.2). There is an array of infrared sensors on the inside of the frame to illuminate the subjects' eyes, and four cameras to follow the eye movement. The vision of the subjects can be recorded using an environment camera on the outside of the frame. The experiment was around 40 min in length. First, the subjects were given a short description of the experiment and a short training period to try navigating in a similar but different virtual environment to get familiar with the set up. Next, the subjects were asked to finish a short demographic survey, and put on the eye-tracking glasses. Following that, the subjects were presented randomly with one of the virtual environment (i.e., positive or negative), and asked to finish the informational and navigational tasks. A short break period was given after each subject finishes the tasks in one environment with a follow up on the other virtual environment. After finishing each environment, the subjects were asked to recall and write down the words they had seen in the environment. There are in total 10 words presented to the subjects, which are separated into two categories, as words that provoke positive emotions (e.g., strong, excited) and those provoke negative emotions (e.g., scared, nervous) [27]. The hypothesis is that the subjects will remember more words (i.e., better performance), and more positive words (comparing to negative words) in the positive environment.

52.4 Result and Discussion

The results of the experiments include two parts (i.e., results of eye-tracking metrics and information recall result). The eye-tracking metrics used in this paper are heat maps, time spent, number of fixations, and time to first fixation. Figure 52.3 shows the heat maps of one subject while he conducted the navigational task to find a thermometer in a specific room. The

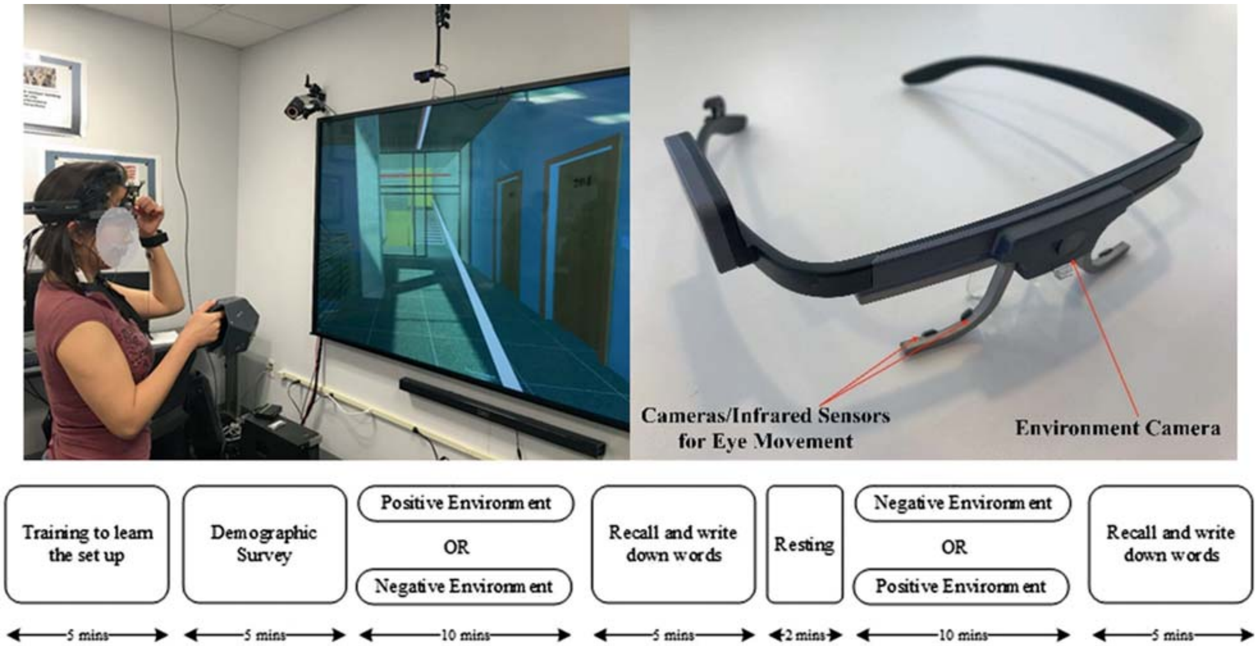

Fig. 52.2 Experiment set up and flow

authors selected a continuous part of the video recorded by the eye-tracking environment camera, where the subjects were exposed to design features evaluated, and compared the heat maps of positive and negative environment. Warmer colors (red) indicate more attention, and cooler colors (green) indicate less attention (as shown in Fig. 52.3). The result shows that in the positive environment (i.e., with ample natural lighting), the subject is more focused on the navigational task (i.e., with one main hot spot in the corridor), whereas in the negative environment (i.e., no natural light with only artificial lighting), the subject showed a more distracted attention with several separated hot spots. Similar analysis was conducted for all participants across all AOIs. The final result shows that all participants had more focused attentions (i.e., less hot spots) for all AOIs.

The authors also conducted data analysis for the other eye-tracking metrics. The results are averaged across 22 participants, and shown in Table 52.4. On average, the subjects showed less time spent in the positive environment for each AOI than the negative one, indicating the subjects were faster on the executing tasks in the positive environment. When the complexity of the tasks is identical, less time spent means higher attention level in the environment [25]. The subjects also had less number of fixations in the positive environment for all AOIs comparing to the negative one. A large number of fixation indicates the task is complex and the subjects showed decreased efficiency in searching and navigating tasks [23]. Subjects showed smaller Time to First Fixation (TTFF) for the AOI: presence of window, level of natural light, and exposure to nature views. TTFF is calculated as the time in milliseconds that the subjects took to notice a specific AOI, and smaller TTFF indicates the high attention level and more focused mind [24].

The authors also analyzed the data obtained from the informational task. For the informational task, the subjects were asked to look at an array of words (total 10 words) on an information panel for 30 s and then recall and write down the words they remember. The words were selected so that they can be clearly separated as positive or negative words that evoke positive/negative human emotions [27]. The words are shown in Table 52.5, separated as positive and negative words. The total number of times that all subjects remembered the words are shown for positive and negative environments. It is clear that in the positive environment, the subjects recalled more words (positive and negative combined) than the negative environment, indicating the positively configured design features had a positive effect on the informational task. From another angle, the positive words were recalled more times than the negative words in the positive environment, meaning the subjects felt more positive emotions in the positive environment. On the other hand, the negative words were recalled more in the negative environment than the positive words. The result of informational task showed that the subjects generally performed better in the positive environment for informational tasks, and the positive environments evoked more positive emotions from the subjects.

Fig. 52.3 Heat map result from one subject's eye-tracking data for AOI amount of natural lighting (left Positive, right Negative). Warmer colors (Red) indicate more attention, and cooler colors (Green) indicate less attention

Table 52.4 Eye-tracking metrics for AOIs in positive/negative environments

AOI	Time spent (s)		Number of fixations (times)		Time to first fixation (ms)	
	Positive	Negative	Positive	Negative	Positive	Negative
Presence of windows	3.0	3.5	268	290	1.0	3.0
Size of windows	3.0	7.0	300	335	5.5	3.8
Level of natural light	5.0	5.4	421	630	1.5	5.2
Exposure to nature view	6.8	8.4	647	902	2.1	2.9

Table 52.5 Count of positive/negative words recalled by subjects in both environments

Word type	Words	Recalled in positive environment (times)	Recalled in negative environment (times)	Total (times)
Positive words	Active	14	9	23
	Strong	16	10	26
	Excited	14	13	27
	Enthusiastic	17	12	29
	Interested	14	12	28
	Total	75	56	131
Negative words	Scared	15	12	27
	Irritable	12	8	20
	Nervous	12	11	23
	Upset	11	17	28
	Distressed	16	9	25
	Total	66	57	123

52.5 Conclusion and Future Work

Architectural design features' impact on human experience has long been argued. Previous research mostly focused on subjective survey studies. This study serves as one of the first studies that aimed at providing empirical quantification on human experience in architectural spaces using an integrated and rapidly replicated VR and eye tracking based data collection. 22 participants were invited to the experiment. The results provide evidence that the presence/size of windows, natural light, and natural views are indeed related to human experience in designed spaces and can positively impact the residents if present. The experimental procedure proposed in this study can be used as a general experimental method for architects to use when collecting user experience data during the design process for improving occupants' experiences. Finally, with more participants, the results could serve as guidelines (i.e., how to correctly configure architectural features) when designing spaces with human experience in mind.

For future work, the study could incorporate other types of body area sensors to provide more detailed human body metrics when experiencing different designs. Another area of improvement can be comparing the results collected from the virtual environments to that of the real environments to investigate the impact of using virtual environments to represent design rather than a real-world building.

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