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Visual Perception: Eye-tracking and Real-time Walkthroughs in Architectural Design

Ming Tang*

School of Architecture and Interior Design, University of Cincinnati, OH 45221, USA

Abstract: This paper discusses the application of Eye Tracking (ET) technologies as a new way for researchers to understand a person's perception of a build environment regarding wayfinding and other spatial features. This method was beneficial for informing reviewers how an existing place or a proposed design was performing in terms of user experience. Combining ET with real-time walkthrough (RTW) and analytical platform allowed designers to make real-time changes and instantly see how these choices affected a user's visual attention and interaction. This paper also presents a study investigating the architectural features emphasizing the simulated human behavioral cues and movement information as input parameters. The research is defined as a hybrid method that seeks augmented architectural experience, wayfinding and analyzes its' performance using ET and RTW. While presenting their concepts through RTW, students used the Tobii Pro eye tracker and analytical software to investigate the attractiveness of the proposed experience related to the five spatial features: face, edge, intensity, blue-yellow contrast, and red-green contrast. The studio projects extended psychological architecture study by exploring, collecting, analyzing, and visualizing behavioral data and using the ET analysis to optimize the design presented through walking and driving simulations. ET allowed students in the transit hub design studio to investigate various design iterations about human perception to enhance spatial organization and navigation.

Keywords: Eye tracking, real-time walkthrough, perception, spatial organization and navigation

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1 INTRODUCTION

Architecture has always been perceived as a collection of the physical environment, intertwined with a psychological layer impacting human behavior. For instance, biophilic design strategies and visual connection to nature in the hospital room can affect a patient's recovery time, and access to the natural daylight in a classroom can affect students' test scores. Through the Academy of Neuroscience for Architecture, Eberhard (2009) presented ways to link neuroscience research to the practice of architecture through sensation and perception, learning and memory, decision-making, emotion and affect, and movement. According to Robinson (2015), neuroscience can truly fertilize architectural thinking and practice by revealing the complex, intricate, overlapping functioning of our sensorimotor systems, by deepening our understanding of how our nervous system binds us to our world, and showing how that world doubles back to shape us.

Eye-tracking (ET) is an emerging method that helps researchers to record a user's visual attention. Across different design fields, ET has become a way of interpreting user experience, which may not be able to be described quantifiably with traditional architectural methods. ET pilot studies have mostly begun to surface within the architectural design field, mostly used in the product and retail design, regarding what elements users are specifically fixating. For instance, through ET analysis of the building environment, people ignore blank facades and bias for curves over straight or sharp lines (Sussman 2019). Measuring these behaviors can be helpful when designers and architects work on space planning and wayfinding.

In recent years, with the development of high-end game engines, such as Unreal, Unity and numerous real-time rendering engines such as Enscape, Lumion, and Twinmotion, traditional architectural visualization has been presented as real-time walkthroughs (RTW). It has never been so easy to design, visualize, and interact with the 3D building information in a real-time environment. With the recent ET technologies and devices such as Tobii Pro glasses, X3-120, and HTC Vive Pro Eye, both RTW and ET are being integrated and reintroduced as powerful visualization and analytical tools for signage and wayfinding design (Tang 2020). As we continue to present building with RTW, how can ET enhance our understanding of our virtual environment perception? As user-centered design increasingly permeates the architecture design field,

*E-mail: tangmg@ucmil.uc.edu

how will these user data-gathering technologies influence architects and augment the traditional design workflow?

2 RESEARCH METHOD ON VISUAL PERCEPTION

One way to simulate the cognitive experience is using an RTW that gives the user the freedom to control the virtual environment through various input devices such as a headset, keyboard, mouse, hand controller, or treadmill. Specifically, these real-time rendering technologies, either through an immersive headset, or large screen, offered a promising platform to study human cognition developed through visual reactions in an interactive environment. The research team could analyze the biological, mechanical system of human visual attention and perception through a virtual environment. The research team has applied RTW with Virtual Reality (VR) and used it in architecture education to provide a sensory experience and create a sense of reality at the University of Cincinnati.

Since, 2017, we have started to combine ET and RTW to test their unique advantages for studying people's visual attention and movement behavior in virtual space. Several architectural design studios and a graduate student thesis were developed under this research scheme. During the early preliminary study, the Tobii Pro X3-120 has been used to capture ET data based on photos of campus buildings. The primary purpose of this early test was to have a better understanding of how participants visually respond to various spatial configurations. The Tobii Pro captured the user's eye movement and recorded the eye fixation duration on the specific area of a photo. Essentially, by using the analytical tools in Tobii studio, the researchers generated a data representation using the Area of Interest (AOI), Bee Swarm (Gaze Pattern), and heat map methods, as shown in Figure 1.

Our analytical method is built on the five visual elements, "face, edge, intensity, blue-yellow contrast, red-green contrast, " which triggers subconscious viewing. These five elements are described as "building blocks of visual attention" in the visual attention software (VAS) by 3M (3M 2020). The path of the user's eye movement and the duration of a user's gaze are different ways in which the analytical algorithm begins to value given stimuli, either captured from a screen-based ET, glasses, or an immersive virtual reality headset. In our method, the Tobii Pro X3-120 was used to conduct user fixations based on existing buildings' photos. We mainly used heat maps, gaze plots, and gaze clusters to understand where the participant was focusing on the first five seconds of looking at a photo. Researchers could break down how each participant's gaze plots and heat maps determined a user's attention on architectural features presented from the duration times and fixation points. After this preliminary test, we applied ET and RTW to the architectural design projects and compared various design iterations and their users' visual attention patterns. Specifically, the "face, edge, intensity, blue-yellow contrast, red-green contrast" is discussed as the five visual elements measured by ET.

2.1 Face

According to Sussman and Hollander (2015), the human brain devotes more area to face recognition than recognizing any other visual object. Physiologically our brains are hardwired to notice other humans within a distance of them. This priority is described by Chalup *et al.* (2010) as face-a-tecture, where the subconscious tends to resemble faces within a structure. The research team confirmed this superior visual feature recognition through ET analysis of the human face within an architectural space. The heat map and gaze cluster data provided direct confirmation of the attention to the human faces, as shown in Figure 2. This significant visual element was later used in the children's library design in a graduate thesis. A playscape of a wall for children to climb up through was created as a part of the discovery play center within the library. In the given design options, one wall was created with a face placed inside it, and the other was not. People were visually attracted to the face more than the one that was designed without the face. This playscape is a

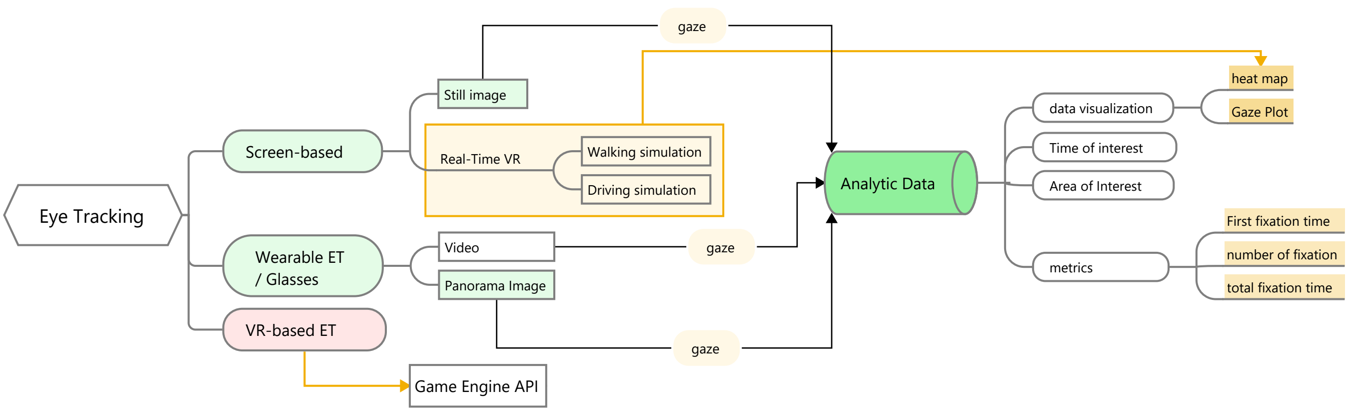

Figure 1. Visual perception measuring framework

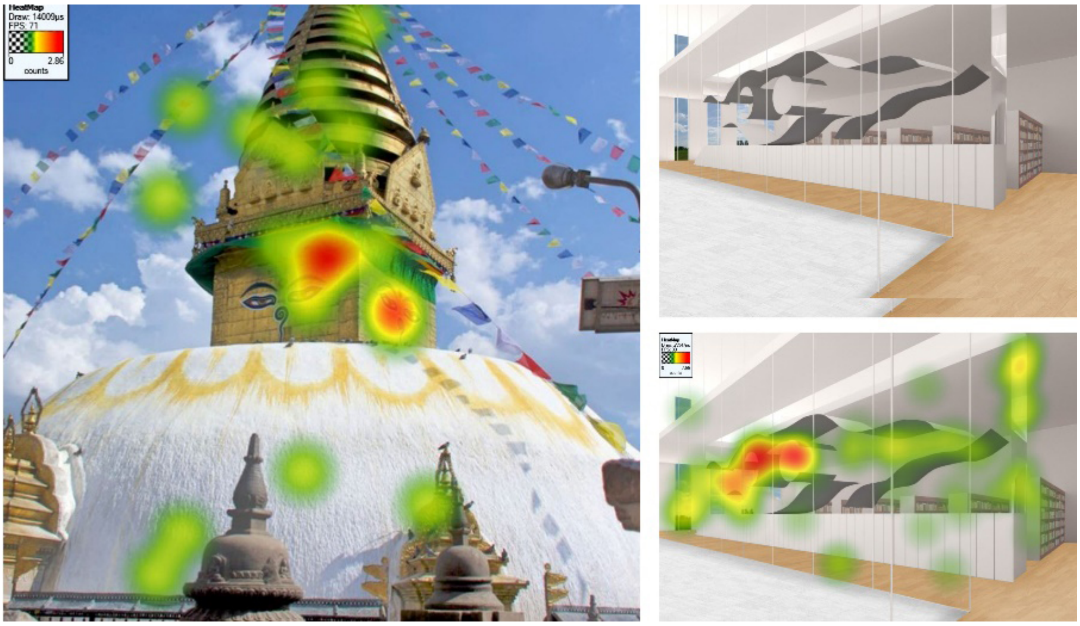

Figure 2. Heat map gaze patterns on the face like shapes

feature within the building. If the design intent was for it to be one of the first things people wanted to use, adding a face like design will give the structure immediate visual attention.

2.2 Edge

Edges work to define the shape that encapsulates the human body in the built environment. Edges, including the horizon, which break the sky and ground in the distant view, can also be "augmented" by changes in material or breaks in pattern. An edge in architecture can be defined as the way that a floor meets a wall, or a wall meets a ceiling. It can also be perceived by the strong linear structural elements such as beams, columns, or stairs, railings, and elevated pathways. Through ET analysis of building photos, we quickly learned that people spent the most time looking at the intersection of edges or parts of the vanishing point that contained more clustered edges than the rest of the building in perspective. Essentially the ET heat map illustrated that people focused on distance and "horizon" areas in the interior than they did look at homogeneous surfaces close to them. As a result of the ET analysis, students used this discovery in their studio project proposals and placed circulation elements like exits and entrances in the concentrated "edge" areas to generate a natural circulation flow, as illustrated in Figure 3. For instance, one student wants the users to focus their attention on the escalator. Looking at the ET results, she noticed attention was being focused on the concentrated beams that lead the gaze to the vanishing point in a distance. She then adjusted her signage and billboard design for one to look upwards at the feature ceiling. Using the ET results, she adjusted sizes and highlighted edges of beams to stand out as a design feature.

2.3 Contrast

As two of the five visual elements affect people's attention, red/green contrast and blue/yellow contrast have a high hue contrast in which colors can be distinctly separated from each other. Students are encouraged to use the two contrasts to help direct people's navigation through the proposed building complex. First, students reinforced previous assumptions on red/green contrast to draw people to exits, entrances, and loading areas for each movement mode. They used gaze clusters to examine a building photo to study if the color contrast could help identify a building entrance, as shown in Figure 4 on the top left side. ET allowed students to examine participant gaze pattern, which helped them better understand users' attention for the red-colored flower bed near the building entrance, and later proposed their wayfinding elements. For instance, one student applied the red color strategy in the pedestrian promenade, including pedestrian entrances and exits, as well as the gateways into the bus loading and vehicular loading in her transit hub project as highlighted in Figure 4 on the top right side. The ET data confirmed the wayfinding performance of the design.

Simplicity and direction of movement are two categories that can be accessed through ET first by observing where a person's gaze is drawn, then by analyzing if their gaze is drawn along the desired pathways or to entry points, and finally, enhancing those points through design to amplify the clarity of direction. One implementation of this approach was illustrated in student design along the building façade and entrance. As seen in the two bottom images in Figure 3, although the typical gaze does proceed along with the building profile, it also heavily focuses on the red-colored bus to the left side and the green trees against the neutral gray building. These are both locations of interest, but the red bus distracts from the actual

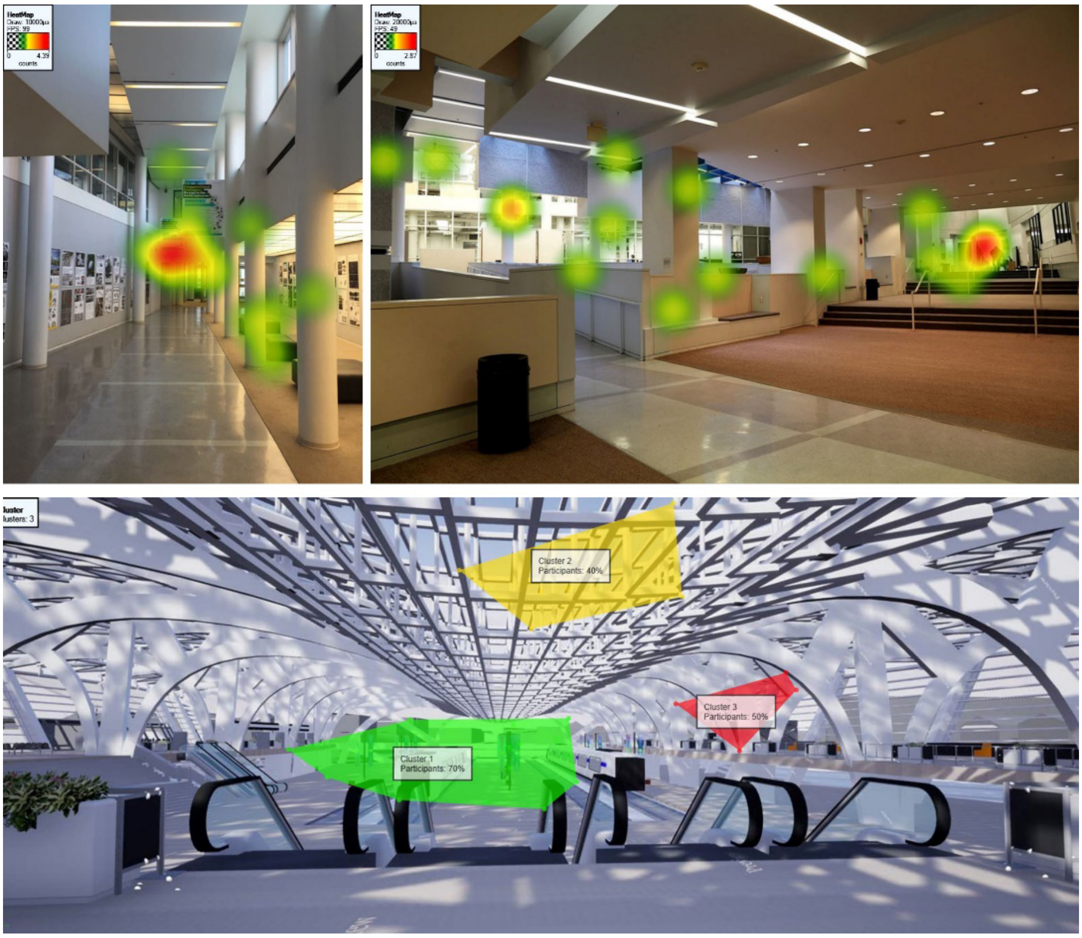

Figure 3. Concentrated "edges" meet at the vanishing point in perspective view

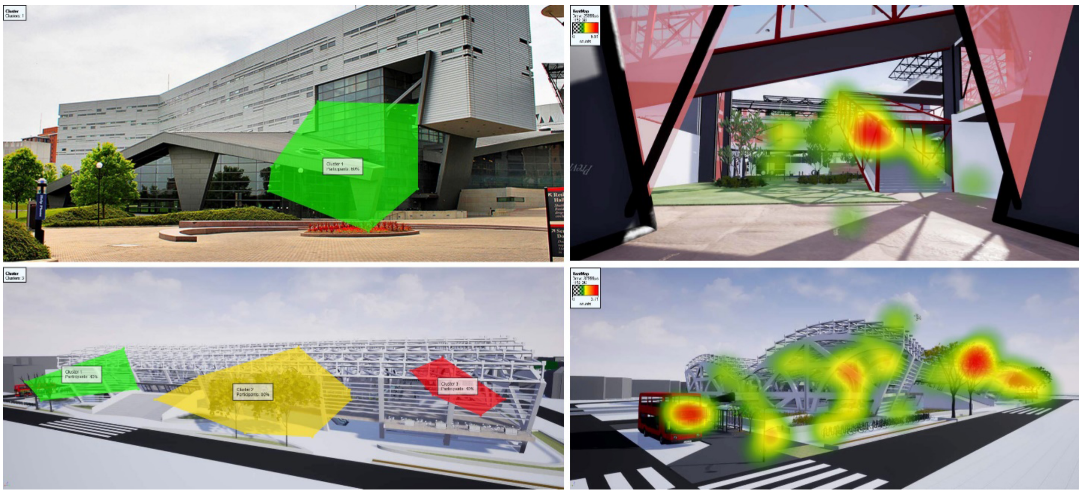

Figure 4. User's gaze fixation and geometric patterns indicating the viewer's attention

front entrance. In contrast, the green trees positively impact the wayfinding. While the person frequently looked toward the peripheral areas of interest, their initial gaze was consistently drawn to the high contrast green trees with bright green colors and other biophilic features.

2.4 Intensity

The intensity can work with color contrast to attract attention. For instance, primary colors are the most "pure" in intensity. Through the preliminary test, we confirmed some signs against the black building façade attracted the user's attention with high intensity, which can be defined as the "saturation" of a hue. It is also noticed that a high intensity without color could attract the eye to the contrast of bright and dark areas in a view. These areas include a dark building profile against a bright sky backdrop or sharp shadows cast by a bright skylight or direct sunlight. For instance, the vertical tower on campus usually draws focus in ET, with its distinct intensity against the bright sky, as shown in Figure 5. The students also use the intensity to create a center of perspective to draw the eye. One student incorporated intensity into the "zebra-stripe" like building skin. To highlight the handrails, stairs, and vertical circulation, he gave them various intensity values through self-illumination materials. He included wayfinding tools such as lighted neon lettering signs, colored lights for the floor texture signifying directional flow of escalators, and signs for the bus and light rail platforms that used saturated color and directional arrows to inform the users of those spaces as shown in Figure 5.

3 TRANSPORTATION HUB DESIGN

To teach ET and RTW applications in architecture, we began the urban mobility studio in, 2019 and designed the Cincinnati Uptown Transportation Hub Center. This project aims to create a new interchange that connects uptown local communities, cities, and states by consolidating public transportation. It is designed to provide a linkage between light rail trains and other modes of transportation such as a hyper-loop, bus rapid transit (BRT), air taxis, passenger cars, bicycles, and scooters. By contrast, most of the existing development of transportation facilities have been carried out individually for a single mode of transportation, resulting in less efficiency and connectivity in terms of the overall transportation network; this "multi-mode transfer center" concentrates transportation in a one-stop solution. Additionally, the cultural, commercial, and business facilities are provided to accommodate the high-volume vehicle and pedestrian flow. Here, the Hyperloop, a high-speed railway, runs interstate and underground with rapid speed, economically, compared to airplanes. It is possible that all the transfers between transportation from the city railroad, metropolitan bus to even future-oriented air taxis take place in the same location. As a complex spatial organization, this hub accommodates many users and with shopping and other cultural and socio-economic draws and will positively impact on the local economy, job creation, and the tourism industry. In the fifteen-week design period, ET with Tobii Pro and RTW with Unreal engine were integrated into the design visualization, evaluation, and optimization process. The five visual elements, "face, edge, intensity, blue-yellow contrast, red-green contrast, " were discussed in students' design proposals.

3.1 Pedestrian Wayfinding Design

The red color serves as an essential ET element in the wayfinding experience at the project Parc (Figure 6). This color is naturally, readily detected by the human eye

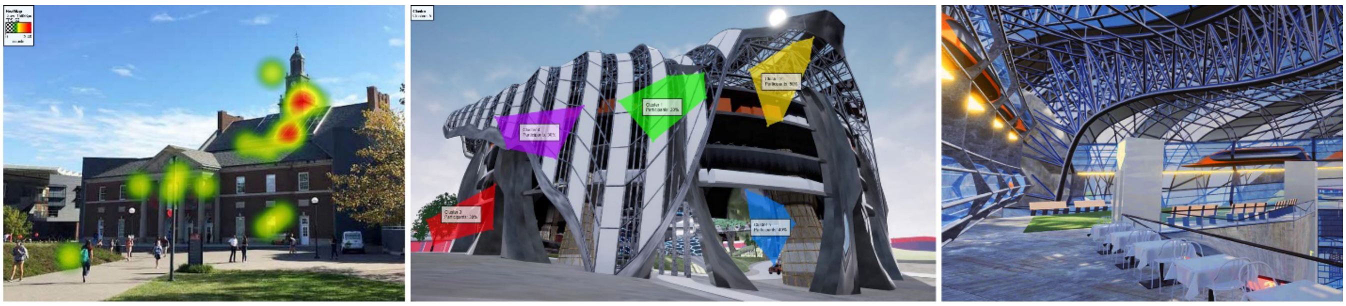

Figure 5. Tower gazing and its intensity against the sky (Left); ET on the zebra patterns of a rendered building (Middle)

Figure 6. Red color as a primary feature of project Parc

and highlights various architectural elements. The virtual walkthrough experience comprises wayfinding oneself through a series of pavilions, circulation paths, green terraces, and ground-level spaces. Commuters also enjoy the Parc as they lounge about the elevated platforms that provide natural elements and prized city views. Amidst the wayfinding elements such as directional signs and video walls which inform about Hyperloop technology and the Tschumi folly, visitors are led to the north-south guideway platform.

With occupying the spaces intertwined with the 40′–60′ tall guideways, finding one's way through the site is synonymous with going on an expedition, as shown in Figure 7. With ET, we confirmed one could perceive the architectural phenomena and how it relates to the surrounding outdoor spaces and complementary site elements. The red color and concentrated edge feature prompt visitors to marvel at where they are within the complex at any given time but also can cause them to desire to explore its many other spaces. RTW and ET automatically call for an immersive and surreal experience, but such an experience is amplified with this project.

3.2 Vehicular Wayfinding Design

The focus of the studio project was creating a series of interconnected pathways for the transit of different types of transportation, for example, cars, buses, bicycles, and pedestrians, while at the same time holding these pathways separate to increase the efficiency of movement and safety of different user groups within the space. All the students were required to create a central pedestrian promenade that soars above and over a set of intersecting paths for vehicle transit to accomplish this. The vehicles can pass underneath or above the promenade at a different level, while a series of escalators and stairs become the vertical link between the load platform and the waiting area. Through ET, we discovered these escalators and stairs often attracted the gaze. To reinforce this linear structure, additional edge elements such as railings, LED lights, and concentered ceilings were designed to guide the gaze into these escalators and stairs without interrupting the previously established attention. This "highlight edge" strategy has generated various benefits for wayfinding. In RTW, these additional elements created reinsurance of vertical paths for people without delaying their movement, as shown in Figure 8.

ET and real-time rendering in the driving simulation have also been discovered to provide first-person experiences in the circulation design for vehicles, as shown in Figure 9. It gave students a real-time experience of where the human eye gaze might fix when a user drives through the designed space. This approach provided the designer a range of spatial design ideas to direct the user's and vehicles' movement within the space in a particular manner, which became crucial while designing the transport hub where the wayfinding design elements were an essential part of the program organization. The use of ET for both driving and walking experiments helped develop and evaluate the design concept to a new level.

3.3 Biophilic Design

The idea started with the use of biophilic design elements as both wayfinding and the stress-relieving element. A green wall was introduced in the initial design phase with the three modes of transport represented using different colored plants to indicate the hub's level at which these transport systems ran. Then an ET experiment was conducted to record and analyze eye movement as participants looked through the rendered images, as shown in Figure 10. It was observed during the ET experiment that the green wall received the maximum heat map intensity confirming that the human eye gaze did observe the use of

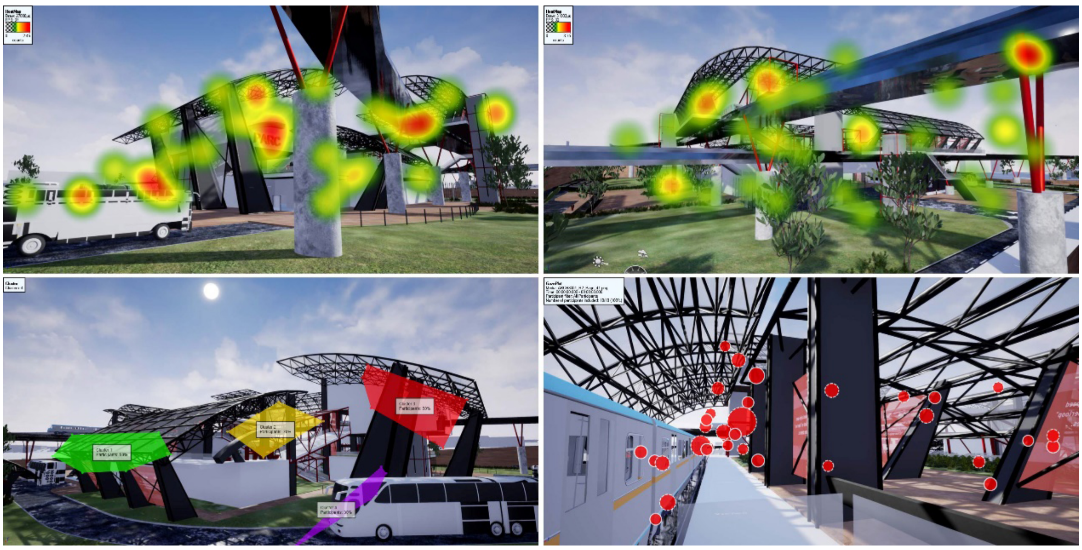

Figure 7. ET applied for the Parc project

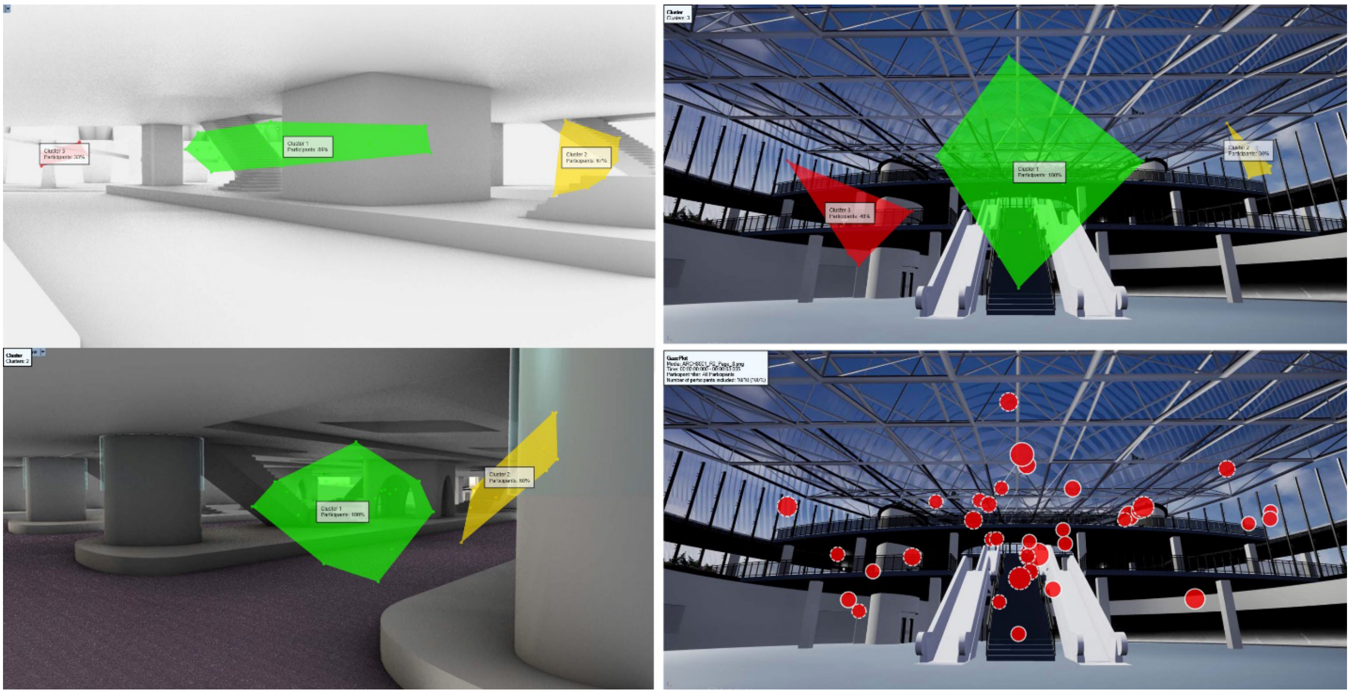

Figure 8. Stairs (left) and escalators (right) attracted visual attention

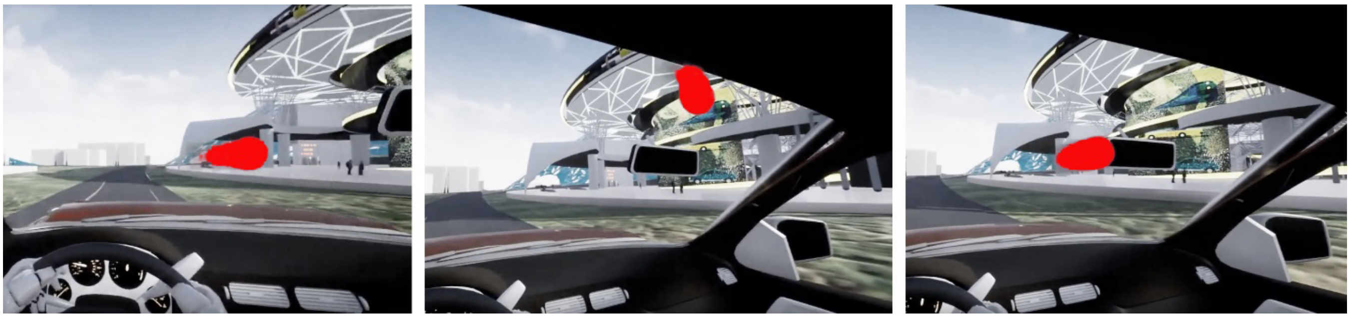

Figure 9. ET gaze data captured in the driving simulation

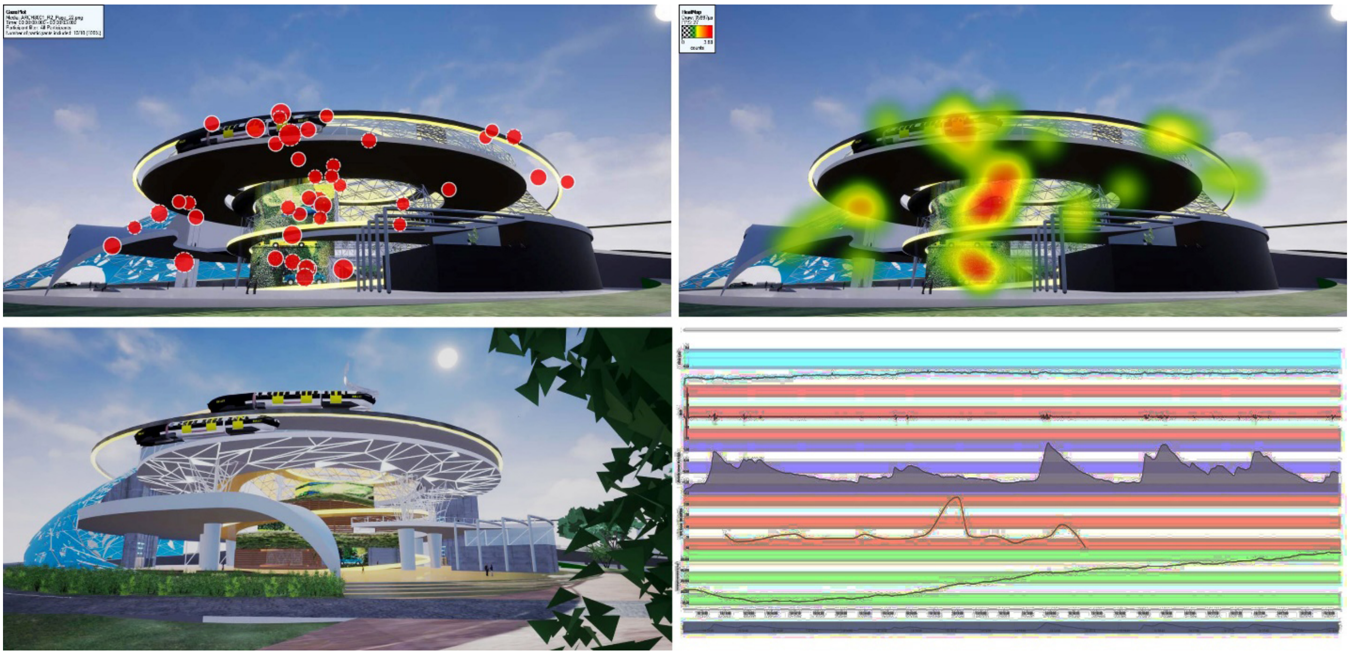

Figure 10. ET data related to the green wall

biophilic elements within the space as a wayfinding tool. The experiment also showed the train's direct visibility. The trains, painted yellow against the blue sky, attracted users' eyes and were used as wayfinding elements.

The green wall and the yellow-colored train station attracted participants' attention. The gaze and AOI analysis confirmed that a significant number of people observed the green wall and its biophilic design elements, and hence, the use of these elements can be considered an effective wayfinding technique. Another reason to use biophilic design elements was to reduce the stress levels of everyday travelers. It has been long observed that natural elements such as plants and trees have a soothing mental effect on humans, and their presence in space can drastically improve spatial appearance and character. Students were introduced to electro-encephalogram (EEG) monitoring for physiological measures. The data had been collected as a device placed on one's wrist to measure skin conductance, heart rate, and blood pressure. Using this information, one could study how another respond to stimuli, using in conjunction with ET. We are investigating if this method could measure what one concentrates on and what design elements provoke stress. As interpretable data, obtaining stress patterns opens opportunities for design wayfinding in a proposed environment drawing on neuroscience.

The final design utilizes this aspect of stress relief, and the structural system is designed to mimic a branching tree with its trunk becoming the columns. This design resulted in a reduction in the user's stress level, which was measured through an Empatica wristband. During the test, participants were asked to navigate the building while wearing an Empatica wristband to measure their stress levels. It was observed that the stress levels had reduced as they approached the biophilic design elements within the building. The bottom right image for Figure 10 represents the physiological measures of stress level. The data show a drop in stress level as the student moves closer to the green walls and tree structure. Another factor to account for in analyzing the success of a design is recording simultaneous ET and physiological data. For example, if a design draws attention to desired locations, but the viewer is stressed out in the process of looking, the purpose of what they are looking at might be clouded, there might be confusion, or there might be a case of sensory overload. When ET data was matched with a stress evaluation, the level of stress detected was typically very high for the first 5–10 seconds, but afterward, it dropped and stayed low for the remainder of the users' experiences. This revealed that while the complexity of space was initially jarring, the simplicity of the overall layout and circulation was understood relatively quickly, and once understood, space was easy to navigate.

4 STUDIO REFLECTION

ET was conducted using both still renderings and RTW. The participants are 30 students with the architectural design major, following the IRB protocol guidelines. For still renderings, a participant was subjected to 3 seconds for his/her gaze to be tracked. The ET and RTW allowed students to evaluate various iterations. They could see what design iteration particularly drew visual attention regarding unique patterns, edges of a continuous form, and areas of high-density contrast and intensity. Students evaluated what forms and depth meant when it came to what participants perceived and were attracted towards. Designing a promenade in a building is often a mental task that takes many hours looking at drawings and 3D models. That is the typical architectural workflow, but using the real-time engine and the VR headset, students were able to walk through the building in the first person. This approach allowed them to understand the wayfinding better. Using the drivable car and walking character with video game controls allowed them to navigate proposed buildings and understand what circulating through the building would be like.

However, there are some concerns in using RTW as a presentation tool for architects. It is important to note the changes in design approach and limitations that RTW entails. One of the most obvious but also most drastic changes is that in an interactive environment, every connection and surface of the building must be developed in connection to the other spaces because all views are accessible to people interacting with the project. Whereas typically, a meticulous set of very developed views is used to portray a project, in RTW, the entire space must tell the project's story. While it has drawbacks, this approach is advantageous because anyone who experiences a building in real life does so by walking through it and observing the spaces in real-time. Although snapshots may have more clarity in the purpose or reason behind the design, that clarity is a false clarity - nowhere in real space does it exist. Thus, although it is much more challenging to tell a story in real-time 3D space, the story told through this mechanism is much closer to the experiential story of the potential building's users.

There are also mixed feedbacks on the ET methods regarding it as an analytical tool for architectural design. Overall, incorporating ET in the design process has been a valuable prospect for architects since its inception, although the plethora of opportunities it brings has obscured for the time being its ideal uses. How to use the raw data of where someone is looking is a design problem, as it ignores how those data are interpreted and acted upon by users. Similarly, RTW provides an interactive, immersive spatial experience. However, in some ways, this overload of sensory input can obscure the fact that it is still an abstract representation of reality, and it is the abstraction that must be understood to take advantage of this interactive media effectively.

In the end, the transit hub project serves as an exciting study of how real-world experimental data of spatial experience can be transferred into design parameters. The struggle to separate the abstract nature of the data due to circumstantial limitations is both pervasive and useful, as it helps to narrow the use of such data in the design process to manageable design choices such as increased or decreased contrast, the use of color, and the placement of foliage and green space. RTW gives a sense of movement and time to otherwise flat spatial projections. It questions the conceptual storytelling approach of typical presentations by revealing that a different story is often told in real-time than is told by jumping from image to image or from plan and section drawings that are never viewed. While the struggle between abstraction and reality continues with ET and stress measurement technologies, the ability to collect actual experiential data during the design process is a prospect that can be used in a constructive and transformative nature. The RTW and ET experience, combined with the gamepad controls, revealed a new aspect of architectural representation, the passage of time that occurs when exploring space. Being in a virtual space better attenuates the perception of the design towards the natural human physiology, requiring the effort to move one's gaze, limiting one's field of view, and the patience required for traversing through the building. As such, RTW is, on the one hand, an expansion of the capabilities of digital representation by incorporating human-like conditions, and on the other hand, it is a limiting factor to how one can move around.

5 CONCLUSIONS

ET combined with RTW in architecture is a promising innovation that has helped designers visualize and evaluate the design in a more quantifiable way. It allows the designer to visualize how the built space would be perceived once constructed. In the case of a transportation hub involving many different modes of transport, it becomes essential to understand the spatial organization and how each model works in tandem with the other. In many design proposals, the three modes of transport are branched into multiple levels, and the user has to use the vertical circulation to reach each level. The levels are often connected through both escalators and elevators for faster vertical transportation across the hub. RTW experiment through space helped understand the time it would take for a traveler to reach from one point in the hub to another, depending on their path. Visual elements of interest were introduced in the path to keep the journey eventful. RTW also helps understand the view of a place from different angles instead of a single rendered image. ET helped students in this project create spaces while experiencing spaces from different angles, allowing for a more analytical approach to design and considering every visual element. ET and RTW provide an effective way of directing a user experience in architectural design and approve that our visual system responds to the five visual elements significantly. The future research will integrate the Tobii pro glasses and the Tobii VR set and explore the relationship between our gaze and our cognitive experience, which can benefit architecture design and wayfinding from the scope of neuroscience.

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