# DETECTING VIRTUAL PERCEPTION BASED ON MULTI-DIMENSIONAL BIOFEEDBACK

*A Method to Pre-Evaluate Architectural Design Objectives*


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**Abstract.** In the information age, the attention to architectural design has gradually shifted from spatial aesthetics to the human's spatial experience. The situation of human perception becomes essential feedback information that designers can use to improve the design schemes. This research proposes an auxiliary method for pre-evaluating the architectural design goals and providing recommendations for architects to optimize the scheme. Specifically, by aggregating and quantitative analyzing electrophysiological signals and eye-tracking data, this research obtained the user's spatial perception with little effect of subjective consciousness as their feedback on the architectural environment. We took the campus outdoor space of an International School of Design as the research sample. By combining the architect's design concept and objectives, we constructed the contrast spatial schemes in virtual reality (VR) for users to experience and analyzed the usability of this method when pre-evaluate design objectives in a practical project.



**Keywords.** Multi-dimensional biofeedback; architectural design objectives; pre-evaluation; virtual reality.


## 1. Introduction

Essentially, under the changeable era, predicting the non-functional qualities like the relationship between space and human emotional perception is more critical than the function and economic benefits of a design. With the development and adoption of new technologies, the information exchanged between human and physical space has become more frequent than before. The mode of architectural design is gradually transferred from architect-oriented to user-oriented. However, related research (Yazdanfar et al., 2015) has shown significant differences in the perception of the same space between designers and ordinary users. Although designers try their best to propose the schemes from the user's viewpoint, it is still difficult to truly fit users' psychological needs.

Since architecture will have long-term impacts on users and will be irreversible once implemented, it is essential for decision-makers and designers to carefully


*PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021*, Volume 2, 183-192.

evaluate whether the design proposals (alternatives) can achieve design goals before arriving at a decision. However, it is generally hard to collect and quantify the user's accurate perceptual and emotional feedback. On the one hand, a common finding in cognitive neuroscience research is that subjective feedback is easily affected by personal preference and professional level. On the other hand, it is difficult for non-professional users to comprehend the design schemes fully. The designers always cannot get users' feedback until completing the construction.

This study proposes a method for assisting design that combines virtual perception and multi-dimensional biofeedback in the detailed design stage to pre-evaluating the realizability of the objectives. By objectively comparing the quantifiable perceptions of users in a simulated environment, the designers can further optimize the schemes. When users experience a designed space in VR, the researchers collected users' physiological data including multi-dimensional electrophysiological signals (EDA: Electrochemical Activity, PPG: photoplethysmography) and eye-movement data which can reflect their visual perception emotional arousal.

## 2. Background

### 2.1. VIRTUAL REALITY AND ARCHITECTURAL SPACE EVALUATION

In 1993, Michael Heim proposed the feasibility of applying VR in architectural design. Some scholars subsequently use VR to assess the design projects and verify the availability of using in collecting feedback. For example, Frost et al. (2000) found that VR allows unprofessional users to figure out what they cannot comprehend through traditional visualization tools (2D and 3D drawings). Westerdahl et al. (2006) compared the VR model with the built environment and found the description of the VR model was entirely accurate. VR allows high-quality visualization of architectural space. It makes irregular space with complex shapes more intuitive and conducive for users to observe complex space' features.

Besides, designers can easily change space elements in VR and form contrast schemes for users to perceive. In 2015, Coronado et al. built three different simulation spaces in VR for evaluation. They showed that VR could bring higher efficiency in the improvement of design schemes. Norouzi et al. (2015) introduced a design platform to harmonize the communication between designers and users in VR. What's more, VR simulates a state of immersion feeling that is highly similar to the real. This VR feature allows researchers to measure psychological, physical, and behavioral responses in a controllable environment. Hence, some research used VR space to induce human emotions. Simultaneously, researchers obtain physiological data using physiological devices to recognize different emotional states according to nerve and cardiac dynamics. This research proved virtual environments could indeed awaken users' emotions such as relaxation or anxiety (Marín-Morales, 2018).

In conclusion, exist research proved physiological sensors could be used in VR experiments to detect the user's emotion when experiencing the space. VR has the potential to become an essential tool for studying the relationship between human perception and architectural space by providing a visual environment with immersion, interactivity, and the capability of inducing emotions.

### 2.2. MULTI-DIMENSIONAL PHYSIOLOGICAL PERCEPTION AND ARCHITECTURAL DESIGN

In the past, research mainly used subjective evaluation methods like interviews or questionnaires on the human spatial perception. The results may involve multiple psychological processes and can be affected by personal factors. Some other research tried to analyze the user's perception through overt behaviors, such as facial expression recognition (FER) and behavioral observation. However, the accuracy of overt behaviors is doubtful because it could be subjectively controlled. The environment can affect the visual perception system and lead to changes in physiological system variables. Physiological parameters are not easy to be controlled by human subjective consciousness and have higher credibility. Using portable physiological instruments and eye trackers can obtain the user's physiological indicators, helping designers objectively comprehend users' feelings of architectural space. According to existing research, skin conductance changes (SCC) and heart rate are nearly related to emotional arousal.

The relevant studies mainly include the following two categories: One uses perceptual measurement technology to identify the spaces that could bring negative emotional experiences (such as stress, anxiety, and fear). In 2020, Lee et al. integrated the on-skin electrophysiological data and location data of multiple people to identify the stress of the elderly caused by environmental obstacles. Some research (Engelniederhammer et al., 2019) observed the impact of crowding on the emotions of pedestrians in high-density urban areas by capturing EDA and skin temperature. The other kind of research used eye-tracking sensor technology to detect the user eyes' position and gaze points. Eye-tracking can get the user's objective feedback information of the designed VR spaces and quickly merge with the user's spatial behavior data to evaluate the scheme.

Since emotional perception and eye tracking can reflect the user's two aspects of "emotion" and "the cause of the emotion," combining these two technologies will help understand perception in a depth feedback mechanism. However, nowadays, little research has proposed applying the perceptual measurement to assist the pre-evaluation of design objectives, and the use of physiological data is relatively single.

## 3. Experiments, Methods and Data Collection

### 3.1. PROJECT BACKGROUND

The experiment sample of this research is the designed campus outdoor space of the ISD. Due to its essential campus location, there are many discussions and controversies regarding the design details during scheme improvement. This campus space designer proposed an axis response to the constructed campus texture and hoped the users could feel the campus spirit when walking along with the dynamic axis space. This axis space's central area spreading to the square in front of the main building is an exclusive space for pedestrians. The designer highlights a vital design objective: increasing the attention of the main building means that when users walk in the central axis space (fig.1), they can observe the main building from a better perspective. The designer hoped to create the depth of the landscape to achieve this aim. “The main building on the central axis becomes a visual focus of constant discovery and approach.” Users in this space are expected to experience the solemn academic atmosphere and have a profound psychological feeling of this university which has a long history.

Figure 1. The general plan and aerial view of the ISD campus area.

At present, this design project is under the discussion and optimization stage. The stakeholders, including school directors, designers, constructors and experts, have launched multiple rounds of seminars, discussing design issues (tab.1) from various perspectives. However, there was some controversy regarding design objectives, which are a brake on the discussion. For one thing, most decision-makers can only predict the design results based on their experience and lack of objective evidence. Besides, due to the differences in multiple backgrounds and standpoints of stakeholders, it is not easy to reach a consensus. Therefore, we established a virtual environment and took this axis space as the testing example. Through analyzing users’ biofeedback, we pre-evaluated design objectives and provided suggestions for resolving controversial design issues.

Table 1. The main argument points of the HITsz-ISD design.

| | **Semi-fixed features** | **The point at issues** |
|---|---|---|
| Axis space | Building elevation | The entrance on the facade visually attractive. |
| | Corridor bridge | The axis space has the depth of field.<br>Increase the attention of the main building.<br>Generate emotional arousal in the axis space.<br>Feel campus culture and arouse emotions during axis space roaming.<br>Have an occlusion on the line of sight. |
| | Landscape belt | Is visually appealing.<br>Lounge seats are easy to find. |
| | Signage system | Is visually appealing. |

## 3.2. COMPARISON SCHEMES

During the multiple rounds of seminars, we collected the issues raised by decision-makers and generated comparison schemes for perception testing according to the project design goals and spatial factors. In this experiment, we set two kinds of comparison; one was a horizontal comparison, including ”experimental space” with corridor bridge and ”control space” without corridor bridge (fig.2). Through analyzing the perception results of the two groups, we can know the influence of the corridor bridge on users and whether the design of these factors can truly reflect the design intent. In the vertical comparison, we measured whether there are significantly different spatial factors’ attention levels to pre-evaluate the design goals.

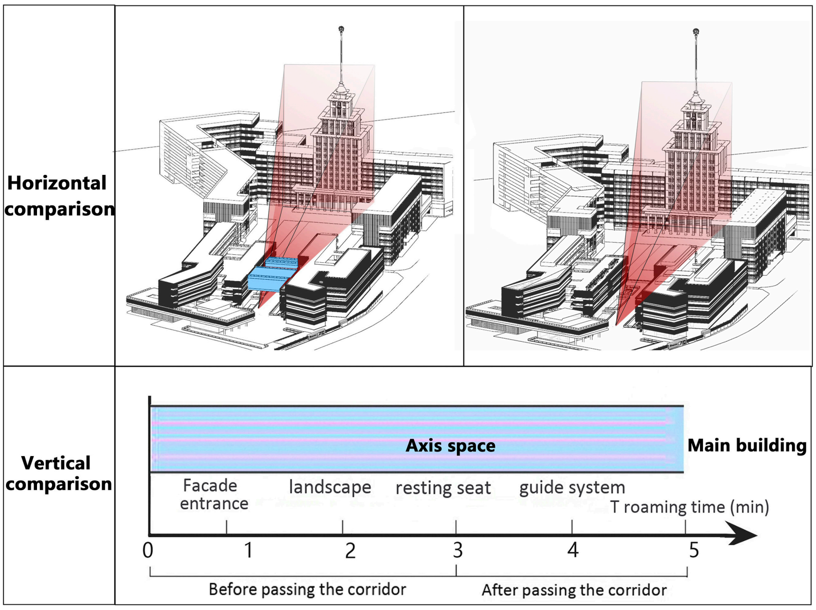


Figure 2. Horizontal and vertical comparison schemes.

## 3.3. EXPERIMENTAL DESIGN

This study adopted the within-participants experiment to reduce the differences between participants. The main disadvantage is that this type of experimental design can cause an accumulative error, which can be solved by balancing the experiment’s order. In this experiment, half of the participants experienced the “control space” first and the other half experienced the “experimental space” space first to offset the impact of experiment sequences.

### *3.3.1. Date collection*

In this experiment, we set two kinds of comparison methods: horizontal comparison and vertical comparison. The horizontal comparison includes ”experimental space” with the corridor bridge and ”control space” without the corridor bridge. We analyzed the perception results of two different spaces to know the influence of the corridor bridge on the users and whether the design of these factors can truly reflect the design intent. In the vertical comparison, we measured the fixation count and duration to determine whether there is significantly different attention between spatial factors and pre-evaluate the design objectives according to the diversity. This research used the Ergo LAB platform (fig.3) to synchronously collect the participants' eye movement data (Tobii Pro Glasses 2), and physiological signals included PPG and EDA during roaming. Integrate collected multi-dimensional physiological data to understand the association between perception and designed environmental elements.


Figure 3. Synchronous collection of multi-dimensional physiological data.

### *3.3.2. Participants*

Since this axis space will open up to social citizens after the building construction is complete (open campus). The type of users could be diversified. We recruited 30 laypersons with no professional design background (16 females, 14 males) by distributing ads on social and online platforms. Participants had not known or experienced this project space before this experiment. They could be potential users of this project and aged between 18 and 40 years old. They were told all possible risks of this experiment before the experiment.

### *3.3.3. Experimental procedure*

The experimental process included the following six stages:

1. Pre-experiment: Invite two postgraduates major in architecture as participants to test the experiment flow and check whether VR spaces were a detailed simulation of the design scheme.
2. Prepare stage: Tell the experiment content and roaming path to participants and

help them wear the sensors and VR eye tracker. Participants need to calm down for about 5 minutes.

3. The first stage: Let participants roam in the “experimental space” for about 5 minutes. Collect physiological signals and eye movement data simultaneously.
4. Time for rest: The participants rest for 10 minutes.
5. The second stage: The second stage: Let participants roam in the “control space” for about 5 minutes. Collect physiological signals and eye movement data simultaneously.
6. Subjective questionnaire: Let participants complete the questionnaires which are used to verify the biofeedback.

## 4. Analysis of Data and Results

This research used basic statistical methods to analyze physiological indicators, including paired-samples T-test and Wilcoxon signed-rank test. We integrated multiple data to obtain feedback on the designed spatial factors by finding significant differences between the perceptions. All statistical calculations were completed in SPSS (version 20.0.0).

### 4.1. HORIZONTAL COMPARISON

#### *4.1.1. Emotional arousal*

This experiment collected participants’ physiological signals, including EDA and PPG. For PPG signal analysis, we chose time-domain indexes containing Mean HR (bpm), SDNN (ms), RMSSD (ms), and frequency-domain index LF/HF. For EDA analysis, the index we chose was SC (μs). A comprehensive analysis of these indicators can better understand the user’s emotional arousal status. According to the results of statistical analysis (tab.2), the users’ emotional arousal in two kinds of axis space (with or without corridors) was not significantly different ($p>0.05$). The corridors had little impact on users’ perception. The existing design objective proposed this axis space will improve the depth and dynamic of view through the design of corridors. However, the result of perception feedback proves that this design goal cannot be realized after is completing construction to a large extent.

Table 2. The analysis of biofeedback data.

| | | N | *MeanHR*(bmp) | *SDNN* (ms) | *RMSSD* (ms) | *LF/HF* | *SC*(μs) |
|---|---|---|---|---|---|---|---|
| Experimental group | Axis space | 30 | 85.83±10.49 | 138.10±124.39 | 178.45±175.74 | 1.31±2.21 | 5.15±5.60 |
| Control group | | 30 | 86.03±10.83 | 122.23±116.26 | 149.99±141.22 | 1.60±1.41 | 5.27±5.73 |
| *t*/*Z* | | | *t*=-.505 | *t*=.469 | *t*=.328 | *Z*=-1.656 | *t*=-.672 |
| *p* | | | .618 | .642 | .746 | .0980* | .507 |

#### *4.1.2. Visual attention to the main building*

This research drew the front elevation of the main building as an area of interest (AOI) to collect eye movement data, including AOI Fixation Count (N) and

Fixation Duration (s), which can well reflect the user's attention to the spatial factors. The participants' attention to the main building was collected while roaming in the axis space. From the statistical analysis result (tab.3), When users experienced various spaces, the number of average fixation counts of the main building was different but was not significant ($p=0.05<0.094<0.1$). Besides, there is no difference in the total fixation duration ($p=0.797>0.1$).

Table 3. Statistical analysis of eye movement data.

| | N | AOI fixation count (N) | AOI Total fixation duration (s) |
|---|---|---|---|
| experimental group | 30 | 86.77±69.73 | .16±.04 |
| Control group | 30 | 73.13±59.34 | .16±.05 |
| t/Z | | t=1.729 | Z=-.257 |
| p | | .094* | .797 |

The "experimental space" was the axis with horizontal corridors. Users cannot see the entire main building at first and gradually broaden the horizon during the roaming. From the eye-tracking feedback, the participants paid more attention to the main building when they roamed the "experimental space" (Fig.4). However, the differences in eye movement data were not significant enough. Designers need to further enhance spatial hierarchy by optimizing the horizontal corridor design or adding other spatial elements to enhance this effect of design further.

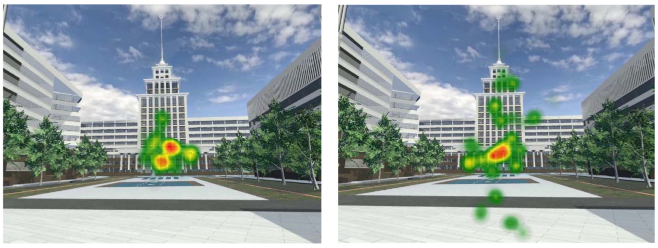

Figure 4. Heat map of users' fixation counts to the main building when walking in different kinds of spaces.

## 4.2. VERTICAL COMPARISON

The vertical comparison mainly analyzed the visual attention of the spatial elements that appear sequentially during the roaming. By analyzing the fixation information of 30 participants. By comparing the AOI data of each spatial element (Fig.5), we found that the main building AOI obtained the highest average fixation counts (N=79.95). Besides, 30 participants paid much attention to the guidance system AOI (N=49.92), even if they had been informed of the roaming path in advance. They spent a long time reading the guide system and bulletin board (Mean fixation duration=0.24s).

However, through replaying the experiment record video, we found that most participants overlooked the building's entrances. The entrances AOI had gain few fixation counts, and the fixation duration was short. This feedback information indicated that the entrance lacked visual appeal, but it may be the result that the participants were told not to enter the building before the experiment. The landscaping stone carving with famous quotes on the ground was a landscape element particularly designed by the designer. Many participants did not notice them when roaming. However, the landscaping stone got a long gaze duration because the participants will stop and read the stone inscriptions verbatim once they notice it. This design element had a particular role in cultural communication, but its' visual significance needs to be improved further.

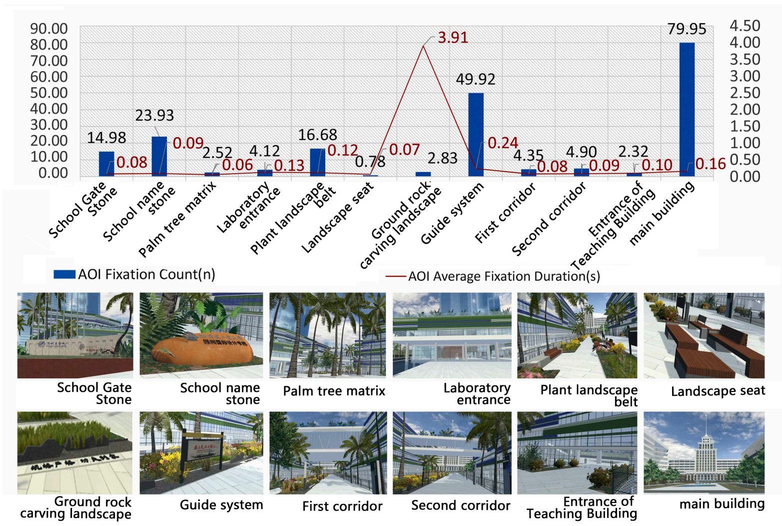


Figure 5. Statistics of eye-movement data on the attention of spatial elements.

## 5. Discussion and conclusion

Although the architects try to design the spaces from the user's perspective, this research found that some design effects may not reach architects' objectives. Architects and ordinary users have a significant difference in their understanding of the same space. Users without experience or professional knowledge have limited knowledge and expression ability of architectural perception, making it difficult for architects to obtain feedback from users and evaluate the objectives of the design scheme. This research collected users' biofeedback in the virtual environment. On the one hand, it provides users with an intuitive presentation to explore and understand the architectural scheme. On the other hand, the designer can flexibly and economically change the environmental factors in VR and obtain feedback from users by constructing the comparison schemes. In the process of improving the actual project, designers no longer need to rely on their empirical judgment or users' vague and non-quantified subjective description to judge whether a design scheme can achieve the design objectives. Physiological data and biofeedback can provide more scientific and objective evidence for scheme optimization. Simultaneously, the evaluation process will not require users to understand professional knowledge or imagine 3D space based on 2D drawings. It can be much easier and more convenient for users to participate in design.

Besides, there are still some shortcomings in this research. Firstly, since the perception of detection requires sensing devices' support and controlled environmental conditions. The laboratory is more suitable for the experiment, which brings inconveniences to users' and designers' participation. Also, most physiological signals can only objectively reflect the degree of the user's emotional arousal instead of accurately determining the emotional type. Therefore, this study could only use subjective questionnaires to verify the biofeedback. In the next research stage, some other physiological detection methods such as Electroencephalogram (EEG) and FER can be used to obtain the user's emotional type.

In conclusion, this research used sensor and computer technology to get biofeedback from users in an emulation VR environment and combine it with the objectives of the design proposal to pre-evaluate architectural spaces. This method is expected to aid in improving design schemes and providing evidence-based recommendations to designers.

## 6. Funding

This work was supported by the National Social Science Fund Later Stage Funding Project. Grant no: 19FXWB026 and the Guangdong Science and Technology Project, Grant no: 2017A020220011. Thanks to the "King far Research Support Program" of King far International Inc. for supporting this study and providing the necessary devices.

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