Biofeedback in the Dynamic VR Environments:

A Method to Evaluate the Influence of Architectural Elements on Human Spatial Perception

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ABSTRACT

Contemporary architecture design is featured by human-oriented. Getting the users' feedback of schemes thus to optimize their positive interactions with spaces is essential to increase designs' quality and attraction. However, uncovering users' true thoughts is challenging because it is difficult for laypersons with no professional design background to describe how architectural elements can affect their emotions. This study aims to use digital technology to comprehend architectural elements' impact on users' perception. Specifically, it combines virtual reality (VR) with biosensing technology to detect users' emotions, guiding designers to improve their design schemes. In this context, to propose a method of evaluation, this research adopted the International School of Design of Harbin Institute of Technology's outdoor spaces as the empirical case. VR had been applied as a visualization tool to construct a dynamic and immersion environment that imitates the campus space. Then some key design elements were changed to form contrast schemes. Participants were recruited to experience these contrast spaces and were collected Electrodermal Activity (EDA) and Photoplethysmography (PPG) signals for emotional arousal analysis. Biofeedback data were analyzed using the paired-samples T-test. The results indicated that some of the design elements did affect users' emotional arousal during roaming; others did not cause a significant difference affection. According to the evaluation result, designers can understand the emotional connection between a design element and users to decide if it needs to be further refined. This research proposed a method that can be used for dynamic and repeatable evaluation of design before the project is completed. Simultaneously, this method can help designers quantitate users' emotional perception and gain the objective basis for design optimization.

CCS CONCEPTS

• **Applied computing**; • **Arts and humanities**; • **Architecture (buildings)**; • **Computer-aided design**;

KEYWORDS

Biofeedback, VR, Dynamic environment, Spatial perception, Architectural design

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1 INTRODUCTION

The spatial perception of human is a multifaceted process, including sensory (mainly visual) stimuli, cognitive processing which eventually influence their subjective evaluation and behavior [1]. Usually, the architectural space is combined by varieties of complex spatial elements. The spatial elements like textured surface, landscape, scale and proportion are the speak way between architectural environment and human. The design concept that architects want to convey to users usually presented through these spatial elements. Therefore, in the processes of scheme generation and optimization, understanding the influence of spatial factors on people's spatial perception plays an important role. On the one hand, architects can assist users to participate in design by collecting their perception feedback. On the other hand, this process can provide basis for architects to optimize the scheme in a targeted way and create an "Experiential Spaces" to better match user's demands in terms of function and symbolism of architecture [2].

Traditional methods involve self-reports, interviews and questionnaires. Even though these methods have some advantages like relatively convenient and easy to get feedback data and has been widely used by researchers [3]. However, for one thing, people's subjective evaluation is easy to be affected by many factors, including the physiological and psychological conditions, their own experience in the period of time under investigation, and even related to knowledge background [4]. Besides, due to the lack of professional architectural knowledge, non-professional users are difficult to understand and image the complex construct way of architectural elements. It is difficult for people to accurately describe the relationship between their spatial perception (such as feelings of pressure, personal preferences, etc.) [5] and the architectural elements. Therefore, it is difficult for the subjective questionnaire to exclude these interfering factors and objectively reflect people's perceptions. The data obtained can be relatively vague and lack accuracy [6].

Generally speaking, architects and researchers need objective evaluation methods because traditional surveys lack effective methods to quantify users' perceptions. Recently, with the speedy development of sensor, biomaterial, and communication technologies, portable physiological signal acquisition device continues to improve [7]. In the neuroscience field, many biometric sensors are being applied to architecture areas which can assist researchers to obtain unbiased data about human physiological, emotional, and cognitive states, such as spatial perception, in various of environments settings [8]. To obtain biofeedback using physiological detection and apply the information to the precise optimization of the design scheme [9], researchers need to control different variables (design features, elements, etc.) under controllable conditions which can be replicated and changed quickly with a high degree of realism [10].

Previous researches showed that the cognitive, behavioral and experiential responses of users are similar in VR and real environment [11, 12]. There is no significant difference between the performance, presence and immersion of participants in the VR and the physical environment. Therefore, VR is a good visual and experimental tool which allow researchers to construct low-risk, cost-efficient, and highly controllable immersive environments for conducting virtual experiments and collecting relevant information.

However, the existing research combining cognitive science, computer technology, and architectural design is still in the initial stages of exploration, especially evaluating the design scheme by quantifying human perception. This study aims to use digital technology to propose an evaluation method that comprehends architectural elements' impact on users' perception more accurately. The research objectives including:

1. Identifying the development of VR and sensor technologies including their applications;
2. Proposing a method to evaluate architectural elements with the assistant of these technologies;
3. Using this method in the evaluation and optimization of a practical design project to discuss its applicability of assisting architectural design and perception-based analysis;
4. Proposing research directions and potential benefits in the future to help further adopt this method for architectural design.

This paper is structured in the following manner. In section 2, existing literatures and related works about applying VR and biofeedback in the architectural area are reviewed. In section 3, combing with an empirical case, we presented a framework of architectural elements' evaluation, which includes the steps dedicated to the presentation of the spaces and change of elements in VR and details related to the collection methods applied to the participants' biofeedback. In section 4, statistical analysis of different signals (EDA and PPG) and emotion recognition of participants who roaming various spaces were presented. The conclusion and future research directions of this work are in section 5.

2 LITERATURE REVIEW

2.1 Dynamic VR Environments

VR is a unique design visualization tool [13] which can immerse the users and illustrate spatial information [14]. Therefore, some studies applied VR to the evaluation of architectural design. For example, Liu et al. [15] showed that VR could attract people to evaluate schemes by reducing the effort required to understand the design. Berg [16] found that evaluation design with virtual environments can better understand the proposed design and improve efficiency. For non-professional users, VR can help them recognize space from a 3D perspective and understand the construction of spatial elements.

Besides, VR can quickly provide immersive visual experiences by constructing simulations of many spaces and environmental elements. Many researchers used VR to explore evidence-based design methods. Nykänen, Porkka, & Kotilainen [17] used VR environments (CAVE) to aid users to participate in the evaluation of hospital spaces factors like colors, windows, surface and materials. Chen, Cui & Hao [18] took the design of age-appropriate color environments as an example and used VR to establish the relationship between the interior color and the health of users' emotion. Cha et al. [19] manipulated ceiling type and height in four different VR environments. They conducted surveys of affective responses to understand the potential of VR for promoting users' participation in design. Some research focused on assessing the influence of using VR in design and participants' subjective feedback. However, according to the "Pygmalion effect" raised by Babbie, when participants are exposed to new technologies like VR, the novelty feeling of it can lead the users to give a higher score to the tested environment [20]. There is a lack of effective methods to quantify the impacts of architectural design elements on human emotional perception, especially to the empirical research.

VR is defined as a computer-generated environment that allows for user interaction and experience through the senses [21]. The application of VR in buildings will enable users to interact more strongly with the design environment, eliciting emotional and psychological responses [22]. Currently, many researchers have found that VR can assist in assessing users' emotional reactions to gain clearer understanding of the designed architecture spaces [23, 24] and to improve design decision-making [25]. In this way, integrating VR and biometric sensors is regarded as an effective method to quantify human biofeedback in VR environments and to integrate into architectural design and evaluation.

2.2 Measuring Spatial Perception in VR

Eberhard proposed that the architectural elements widely impact human perception in a space and different design features have different influence on specific experience [26]. For instance, some research concluded that human perception emotion (stress and anxiety levels) can be influenced by lighting and level of luminance [27]. Because the human's brain activations is considered more objective indicators to reflect humans' sense of presence in VR environment. However, it is difficult to use EEG devices in experiments because they are costly, cumbersome, and difficult to operate [28]. Many researches show that there are noticeable correlation between perception and emotions of the participants when immersed in virtual environments [29], another approach to measure spatial perception is through collecting emotional response.

Various metrics include heart rate, blood pressure have been recommended to comprehend the influence of architectural design elements on emotional and physiological states of users [30]. These metrics can easy be collected by many biometric sensors which can be combined with VR for the detection and quantification of users' emotional experience. Some measuring instruments based on information science and sensor technology, such as portable

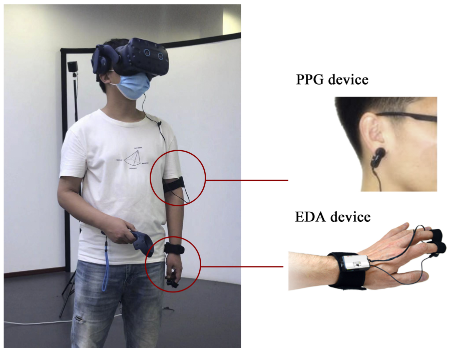

Figure 1: Common biometric sensors

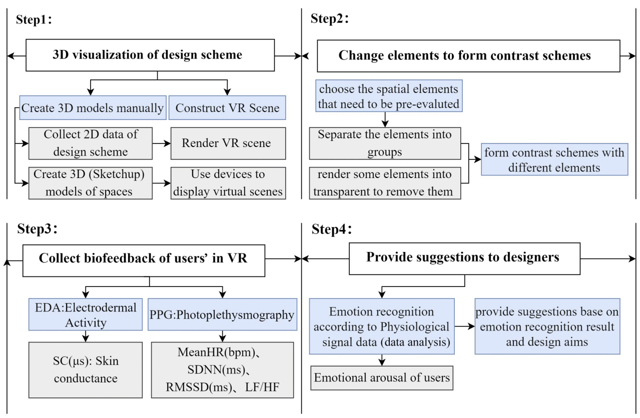

Figure 2: The proposed evaluation workflow

physiological sensors, can respond to user movements and provide real-time sensory feedback. Most widely used biometric tools including the EDA and PPG (Figure 1). Dias et al. used EDA and EMG sensors to detect different emotion of users when they face eight kinds of designed VR environment [31]; Ergan et al. used EEG, GSR, and PPG sensors to measure the stress and anxiety feeling when in the spaces with different design features [32]. In conclusion, sensing technology combined with VR is expected to measure human's emotional perception more accurately and objectively to better assist the users and designers in pre-evaluating schemes.

3 METHOD

3.1 The Evaluation Workflow

The evaluation process mainly includes four stages (Figure 2), including the visualization of design scheme, the construction of contrast schemes in VR, the collection of physiological feedback data collection, analyzing data to provide the suggestions combined with design objectives.

This research is mainly aimed at the unbuilt spaces, which in the scheme design stage. Manual modeling can realize the simulation of spaces and real-time adjustment of the spatial elements. Before developing the virtual environment, we firstly constructed SketchUp models according to the scheme. After which, this study

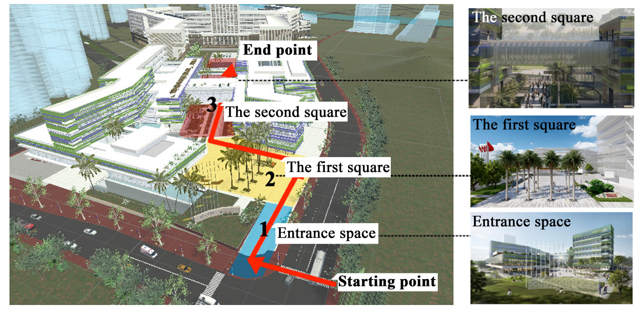

Figure 3: Roam path of HITsz-ISD (design scheme from GDAD &Ateliers 234)

uses Unity3D software to build the VR scene. The Unity3D supports FBR mapping and lighting settings giving the virtual materials a realistic light, texture, and color, which are the foundation for the users to have a real experience. What is more, Unity3D meets perceptual detection hardware equipment's compatibility requirements.

The emotion recognition in this study is based on physiological signal analysis. Generally, it mainly includes four steps: collecting physiological signals, preprocessing physiological signals, extracting signal features, and analyzing emotional arousal. In this study, EDA and PPG, the two most commonly used and stable physiological indicators in emotion recognition were selected [33]. We used Ergo LAB man-machine environment synchronization platform to collect the changes of EDA and PPG parameters of users in realtime, preprocess data, and select data fragments to filter and extract meaningful data results.

3.2 The Research of Empirical Case

Steen Eiler Rasmussen, a Danish architectural phenomenologist, insisted in his book "Experience Architecture" that movement, perspective, and active perception are essential to experience the built environment [34]. He believes that the quality and evaluation of architectural spaces are actively perceived by users in time and movement. Therefore, in this study, we selected a relatively complete campus outdoor space sequence (Figure 3) of Harbin Institute of Technology Shenzhen, School of International Design (HITsz-ISD). It is in the scheme design stage and can be used for active roaming by users in VR.

The architects designed several essential spatial elements to enhance the space's metaphor and level on this spatial sequence. In our preliminary study, we organized users to roam in the virtual sequence space. We added or subtracted these elements to form comparative schemes and collected biofeedback data from users. The experiment's main aim was to know whether these design factors impact users' spatial perception and whether architects' concept can be realized by designing these spatial factors.

3.2.1 Develop Virtual Environment. To develop the virtual environment, we constructed SketchUp models first for HITsz-ISD according to the scheme and create a VR environment using Unity 3D. The space sample is the outdoor campus space of HITsz-ISD, a critical sequence space that begins from the entrance space to

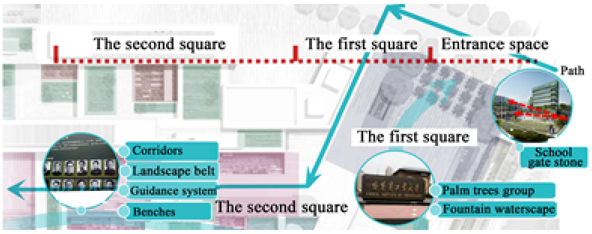

Figure 4: Important spatial elements

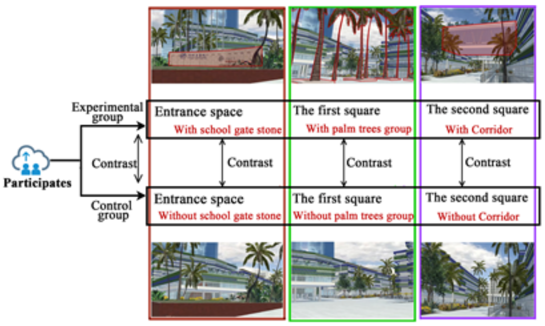

Figure 5: Experimental and control groups

the first square to the second square and the square in front of the main building. The architects' intention of these spaces is to allow users to experience the campus spirit and spatial metaphors through roaming and generate emotional awakening.

In this dynamic spatial sequence, there are three critical spatial nodes: the entrance space, the first square, and the second square (Figure 4). In the preliminary study, we selected the school gate stone in the entrance space, the palm trees group in the first square, and the horizontal corridors in the second square as the variable elements. These factors will have a relatively large impact on the user's visual perception and emotional situation.

VR provides dynamic environments that can quickly iterate and form comparison designs by moving, editing, deleting, or adding objects. For the roaming path of the control group, we removed these three essential factors. On the contrary, we added these three factors to the experimental group (Figure 5). Through repeated experiments, we let users experience these two groups and collected physiological data simultaneously. By comparing the two perception experience results, the existence and nonexistence of these three factors are analyzed to verify the influence of the user's spatial perception and feedback to confirm whether these factors can truly reflect the design intent.

3.2.2 Participants. In this study, through the distribution of recruitment information on social platforms and online platforms, a total of 30 participants (16 female, 14 male) were recruited, aged between 18 and 40. The participants' conditions in the experiment were normal vision and no diseases such as heart disease or vertigo. Participants had not experienced this space sample before the experiment. They knew the possible risks of the investigation before the experiment and signed an agreement.

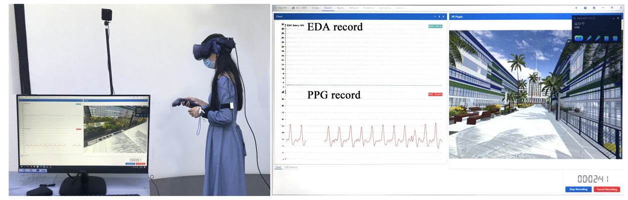

Figure 6: Ergo LAB platform used to collect biofeedback in VR

This experiment uses within-subjects design, which is also called within-groups design in psychological research. Each participant has to conduct experiments with all conditions which can eliminate or reduce the errors caused by differences between subjects. However, participants have to go through from one condition to another which will cause accumulative error. The way to eliminate this error is to balance the sequence of experiments. Therefore, in this study, 15 subjects will first roam the control group and then the experimental group; the other 15 participants will wander in reverse order to offset the influence of sequence.

3.2.3 Experimental Equipment. This research uses the Ergo LAB human-machine environment synchronization platform. The platform's VR experimental stimulus module can provide 3D completely immersed VR space constructed by the researchers to participate. Wearable sensors technology allows the monitoring of several psychophysiological responses in real-time. The physiological recording module can collect the user's EDA, PPG, and other multi-dimensional physiological indicators during the roam time. The researchers can then analyze the participants' emotional and physiological changes (Figure 6).

3.2.4 Design of Experimental Process. The formal experimental process design mainly includes the following five stages:

1. The preparation stage: explain the experiment process to the participants and help them wear physiological sensor devices (EDA and PPG) and VR helmets to enter the virtual environment. At the starting point, the subject needs to calm down for about 5 minutes.
2. The first stage of the experiment: let participants roam along the tested spatial sequence path for the first time. The device synchronously records and collects physiological signals, and the whole roaming process takes about 5 minutes.
3. Rest: let participates rest for about 10 minutes, switch VR scenes and check whether the first stage's physiological data is complete and usable.
4. The second stage of the experiment: let participants roam along the tested spatial sequence path for the second time. The device synchronously records and collects physiological signals, and the whole roaming process takes about 5 minutes.
5. Finish subjective questionnaire: help participant removes the devices and let him (her) complete the subjective questionnaire, which is used to verify and assist in analyzing biofeedback data. This process takes about 10 minutes.

Table 1: Features of used common biometric sensors

Sensors	Primary data	Valence or arousal	Effort required to analyze data	Focus	Indicators
EDA	Electrodermal Activity	Arousal	Medium	Response of Skin conductance	SC (μs)
PPG	Heart activity	Arousal	Medium	HRV Change	Mean HR (bpm), SDNN (ms), and RMSSD (ms), LF/HF

4 DATA ANALYSIS

4.1 Physiological Indexes and Emotion Recognition

After completing the experiment, we counted participates' biofeedback data in the roaming process and performed a systematic analysis. We replayed the participant's experimental video, marked the time stamp on the entire roaming track, and delineated the period according to the participant's position in the3D space scene. After that, we then exported the data in segments to obtain the subjects' physiological perception data when they roamed in the three spaces on the path.

We selected some indicators of EDA and PPG for emotion recognition (Table 1). The time-domain indicators chosen for the PPG are Mean HR (bpm), SDNN (ms), and RMSSD (ms), which are near related to the degree of emotional arousal. The frequency-domain indicators are the ratio of LF and HF, which shows the balance of sympathetic and parasympathetic activities. Mean HR can describe the change of heart rate. The larger value of the SDNN indicator means the higher heart rate variability. RMSSD is an index representing parasympathetic nerve excitement, and the value decreases when the activity of parasympathetic nerve decreases. LF/HF shows the balance of sympathetic nerve and parasympathetic nerve activity. The smaller the ratio, the more balanced the emotional state of the person. The most commonly used time-domain indicator of EDA is the SC (μs). An increase of SC reflects an increase in emotional arousal, and a decrease represents a decrease in emotional arousal.

4.2 Statistic Analysis of Data

This research used the SPSS to analyze the collected data. After processing extreme values, we used a test of normality to determine whether the data population obeys normal distribution. When the data fit the normal distribution, we use the Paired-Samples T-test; otherwise, we use the Wilcoxon sign-rank test. Statistical analysis (Table 2) result showed that there was no significant difference in emotional arousal between the experimental group and the control group ($p>0.05$) in three spaces. The second square's LF/HF ratio was different but not significant ($0.05<p<0.1$).

We calculated and analyzed the average of various physiological data indicators. The following data (Figure 7) showed that, in the entrance space, during the experience of the experimental group space, the Mean HR, SDNN, SC, and LF/HF values of 30 subjects are higher, while the RMSSD value was lower. When 30 participates roamed the entrance space with the school gate stone, the emotional arousal level was higher. In the first square, the mean HR, SC, LF/HF values of the 30 subjects in the experimental group were lower, while the RMSSD value was higher. Participants had a higher degree of emotional arousal when roaming without palm trees group. From the perspective of spatial design, palm trees may affect space's openness and block the line of sight. In the second square space, the emotional arousal of the 30 participants was higher in the square without the corridor, and the LF/HF values were statistically different.

In summary, although the 30 participants had different levels of emotional arousal when experiencing the spaces containing different architectural elements. However, the design of each spatial factor's main factors failed to significantly arouse users' emotional arousal on a statistical level, showing that the main factors' existing design has some deficiencies. For instance, the school gate stone failed to realize the architect's idea; that is, the school gate's large-scale stone can allow users to enter the main campus space to form a clear impression and feeling of reverence for the campus. The architect initially intended to create the first impression of the campus through the Palm trees group. However, according to the experiment's result, this design did not produce significant effects. The Palm trees group also failed to arouse the user's emotional arousal.

5 DISCUSSION AND CONCLUSION

This research combined VR and biofeedback to conduct a preliminary study about the influence of architectural elements on users' spatial perception. The proposed method could improve the existing evaluation process of participatory design in many respects. First of all, by taking a real project as an empirical case, we found that researchers can quickly add, subtract or change the spatial factors and their features that need to be tested. After which, researchers can construct comparison schemes for users to perceive and experience in the immersive environment. This can remedy the traditional architectural evaluation shortage. For example, for users, generating similar perceptions like immersing in 3D spaces only basing on 2D drawings or models was difficult before the scheme is completed. Using this evaluation method, users can roam and explore the VR spaces by themselves, increasing their interest and encouraging them to participate in architectural design that may not be their familiar area.

Besides, designers can have more efficient and flexible visualization methods for real-time iteration or comparison of designs. This evaluation method used sensing technology that supports the objective and accurate measurement of the human perceptual experience. This allows the designer to obtain quantifiable users' biofeedback, which further extracts useful information and gets suggestions.

Table 2: Analysis results of three spatial biofeedback data

		N	Mean HR (bmp)	SDNN (ms)	RMSSD (ms)	LF/HF	SC(μs)
Entrance space	experimental group	30	85.07±10.44	119.43±137.91	157.05±196.24	2.28±2.21	5.74±5.67
	Control group	30	84.73±9.58	119.18±105.61	163.93±190.23	1.84±1.61	5.61±5.67
	t/Z		Z=-.321	Z=-.381	Z=-.463	Z=-1.327	t=.392
	p		.748	.704	.644	.185	.698
The first square	experimental group	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		Z=-.127	t=.603	t=.817	t=-1.144	Z=.668
	p		.899	.552	.421	.262	.504
The second square	experimental group	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

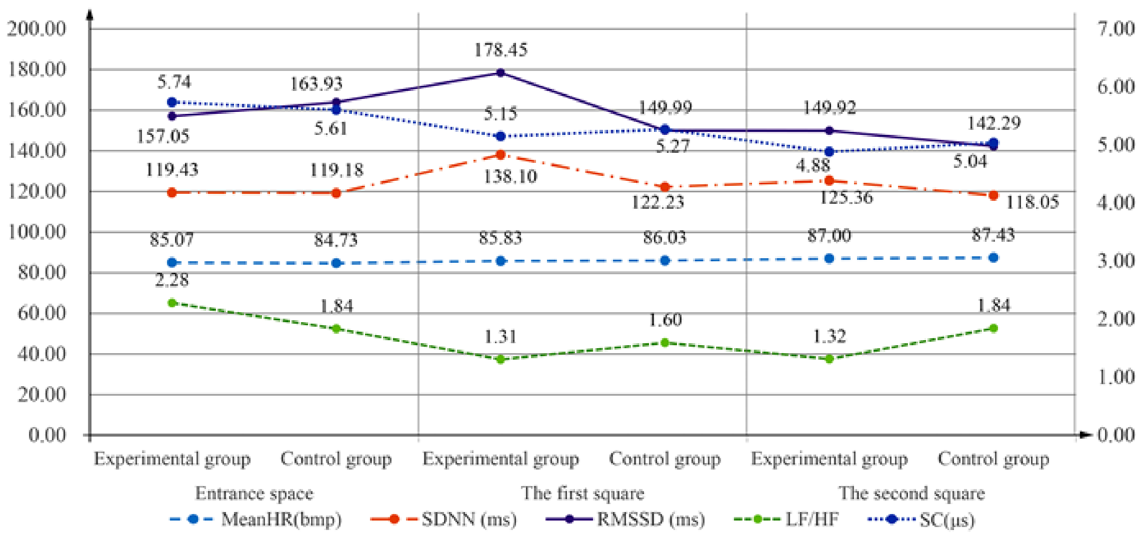

Figure 7: Comparison of the average of various physiological data indicators

With the combination of VR and sensing technology, this method will provide new ideas for architects who wish to convey a sense of the experience and optimize people-oriented design schemes.

This preliminary research also has some deficiencies. On the one hand, even though the indicators of EDA and PPG are easy for data collection and analysis. These two kinds of indicators can only reflect arousal but not Valence, that is, cannot judge emotion type. This question can only be solved by using subjective questionnaires for the supplementary survey currently. In the future studies, this problem can be optimized by using EEG and facial expression recognition. On the other hand, the multidimensional physiological sensing equipment and analysis system are relatively expensive and challenging to popularize quickly. Meanwhile, it has high requirements for simulation of the model and VR environment. At the same time, the physiological signal collection process is susceptible to the environment. Since physiological detection of VR environment requires equipment support, the experiment can only be held in the laboratory with equipment and controllable environmental conditions, limiting the participation of a mass of users.

In the future research, various types of architectural spaces will be evaluated using this method to verify the application range. Besides, comparing the evaluation result in VR and real environment after the design project completed is also a topic worthy of further study. With the development of big data, wireless network technology, and wearable biofeedback experimental equipment, the advantage like having portable sensing device support, real-time interactive information transmission, and Internet data collection is expected to add to this evaluation method. The relationship between the users' perception and space elements' features can be summarized by aggregating an amount of data. This can be an auxiliary evaluation tool to help the researchers optimize the architectural design and make the architectural design process more humane and scientific.

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