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Visual Experimentation Research on Traditional Residential Courtyard Spaces Using Virtual Eye-Tracking Technology

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Abstract: Courtyard space serves as the soul of traditional residences in Southern China, representing a gem in traditional Chinese architecture. Courtyards play a multifaceted role in architecture, including functions such as lighting, ventilation, water collection, solar radiation, and environmental beautification. This paper, building upon previous research and theoretical foundations, takes three types of courtyards in "Kong House" as the research subjects. Through methods like data collection, literature analysis, questionnaire surveys, and eye-tracking experiments, the study investigates the spatial experience of courtyard spaces in traditional residences. It quantitatively validates the design theory of courtyard spaces, analyzes the similarities and differences in spatial experiences among comprehensive courtyards, landscape courtyards, and functional courtyards, and concludes the study. The experiments indicate that incorporating courtyard spaces in traditional residences can effectively influence human behavior patterns and perceptual choices. Comprehensive courtyards typically stimulate more exploration and lingering behaviors. The combination of virtual reality and eye-tracking experiments provides valuable visual information and statistical data for analyzing human behavior and evaluating traditional residential design schemes.

Keywords: Traditional Residence, Courtyard Space, Virtual Reality, Eye Tracking, Subjective Evaluation Method

1. Introduction

Courtyards are a common spatial form in traditional dwellings in southern China and are one of the essential spaces in traditional Chinese architecture. However, with the acceleration of modernization and urbanization, more and more traditional dwellings are being demolished, and the courtyard spaces within them are disappearing.

With the development of the economy and the improvement of people's living standards, there is a growing desire for a better and higher quality of life. The relationship between architecture and the environment, theories on gray spaces, and other aspects are gradually gaining attention. Architecture is no longer merely pursuing the rational arrangement of functions but is placing greater emphasis on spatial quality. In this context, courtyard spaces, as a form of "ambiguous space," are gradually gaining attention. The aesthetic, environmental, and landscape significance of courtyard spaces is being rediscovered.

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In recent years, with the continuous and in-depth development of research in the field of architectural studies, interdisciplinary research is gaining increasing attention. The field of architecture has achieved fruitful results by incorporating research methods from psychology, particularly in environmental psychology. Using experimental methods from psychology, extensive research has been conducted in directions such as human subjective spatial perception [1]. Contemporary research on courtyard space design theory is already quite rich, but much of it involves analysis through traditional architectural theories or qualitative approaches analyzing spatial qualities through case studies. Earlier research on analyzing human behavior involved employing multi-agent-based simulations and conducting on-site observations through manual labor or surveillance methods (such as cameras, Wi-Fi, UWB, and Bluetooth) [2]. These approaches either struggle to replicate realistic, intricate behaviors or necessitate rigorous field trials, depend on a physically constructed environment, and pose difficulties when applied in the conceptual design stage [3]. Therefore, measuring and analyzing the interaction of user behavior with the courtyard spaces in traditional residence design has long been an important challenge.

This study, by collecting existing research literature on courtyard spaces, aims to understand analyses of courtyard space qualities and design methods within the context of traditional architectural theories. In the laboratory, virtual eye-tracking experiments are conducted to obtain visual perceptual experience data of individuals in different types of courtyard spaces. Finally, a questionnaire survey is employed to gather subjective evaluations of people regarding the spatial qualities of different types of courtyard spaces. The collected data is then analyzed quantitatively to explore the specific effects of courtyard spaces.

The experimental investigation of courtyard space design techniques and spatial qualities has several objectives: 1) Through emerging experimental methods, analyze individuals' subjective feelings and spatial experiences in courtyard spaces. Establish experimental groups with courtyards and control groups without courtyards to quantitatively verify the design theories of traditional residential courtyards. 2) Compared to other methods, eye-tracking can measure visual attention, thereby providing rich sources of cognitive information and transforming raw eye-tracking data into parameters suitable for analysis [4]. Collect eye-tracking data of individuals in courtyard spaces to quantitatively explore the impact of courtyard spaces on people's spatial experiences. 3) Compare the spatial cognitive differences of individuals in traditional residential courtyards with three different patterns, comparing the similarities and differences in spatial qualities of different types of courtyards. 4) Summarize courtyard space design principles suitable for modern architectural design and rural residential design. Investigate how architectural design, in the process of drawing on traditional courtyard space design techniques, can inherit its essence.

Conducting quantitative research on courtyard spaces using a virtual eye-tracking device holds substantial significance. This study can objectively record participants' visual focal points in courtyard spaces, providing accurate data support. It deepens the researchers' understanding of the actual behaviors and perceptual modes of individuals in courtyards, subsequently enabling the evaluation of the guidance effects of courtyard designs. Simultaneously, this study can assist architects in promptly receiving user feedback during the design process, offering guidance for more human-centric design and optimization of courtyard spaces. It holds the potential to enhance the quality of interaction between architectural environments and people [5].

2. Basic Concepts

The ancient geographic concept of ‘skywells’ originates from Sun Tzu's "The Art of War," Here, ‘skywells’ is explained as a naturally steep-walled well with water converging from all sides. In architecture, ‘skywells’ refers to an open space enclosed between buildings or between a building and a wall. The typical defining elements are four or three, meaning enclosed on four sides or three

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sides. This structure creates a generalized space resembling a well, distinct from the geological definition.

2.1. Characteristics of Skywells Space

The base defines a space; architectural space typically consists of a bottom, a top, and no enclosed interfaces. Typically, a Skywells is an outdoor space without a top. Unlike yards, Skywells courtyard is smaller with fewer elements. In the study of residential Skywells, their functions include lighting, ventilation, space organization, sense of place, and cultural connotations. Ventilation and lighting are fundamental functions. Skywells courtyards are usually the center of a building, organizing various spaces in an orderly manner. As an outdoor space within a building, courtyards possess certain place characteristics through enclosed interfaces, centripetal force, and diverse variations. In residential exploration, Skywells serve as gathering places for family communication, promoting emotional exchange. In ancient public buildings such as ancestral halls, Skywells courtyards are venues for rituals and celebrations. Historically, Skywells courtyards have become carriers of China's traditional residential spiritual and cultural heritage.

2.2. Skywells Space in Traditional Residences

Skywell, prevalent in the south for ventilation and lighting, is seen in Hui-style architecture, Miao stilted houses, and modern Guangdong diaolou and arcade buildings.

In traditional Chinese residential dwellings, besides providing ventilation and lighting, courtyards, with the improvement of residential architecture and people's quality of life, have differentiated into various functional features: landscape-type courtyards, functional courtyards (basic ventilation and lighting functions), and integrated courtyards.

Landscape-type Courtyards: When the space in residential homes is large enough, homeowners with aesthetic preferences typically detach courtyards from the building's usable area and incorporate them into a landscape setting. From the perspective of environmental psychology, the transformation of courtyard space by individuals brings about changes in the environment. Simultaneously, changes in the environment influence human psychology and behavior. For example, the landscape in courtyards enriches people's visual perceptual experience, and the spiritual aspect of the spatial environment affects human psychology and behavior.

Integrated Courtyards: This type of courtyard integrates the advantages of landscape-type courtyards and functional courtyards. Generally, it carries more functions and, while meeting basic functional requirements, also combines ornamental and centripetal activity functions, resulting in a stronger sense of place.

Functional Courtyards: This type of courtyard prioritizes the functional advantages. For example, a courtyard was formed by enlarging the stairwell to provide lighting and ventilation for the stairwell. Such courtyards often have a smaller scale.

3. Methodology

Now, in the era of big data, an increasing number of experimental, observational, and computer analysis methods are introduced into the study of spatial cognition. These methods provide a perspective of complex systems to depict the mutual influence between individuals and space. The core technology of dynamic experiments is eye-tracking technology. Eye tracking refers to the process of automatically detecting the center of the pupil or identifying the three-dimensional line of sight direction and fixation points [6]. This is achieved through instrument processing technology, locating the pupil position, obtaining coordinates, and, through specific algorithms, deriving data such as blink frequency, pupil data, and fixation time data of the subjects.Virtual Reality (VR)

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technology involves creating artificial, three-dimensional virtual environments that allow users to interact with objects within the virtual environment in a natural and immersive manner [7].

VR (Virtual Reality) eye-tracking experiments involve users entering a virtual environment using VR head-mounted eye-tracking devices for eye movement tracking. Established in the 1960s and 1970s, "Environmental Behavior Studies" is an important field of research in spatial cognition. It emphasizes the observable behaviors of individuals in the environment but pays less attention to exploring the psychological mechanisms behind these behaviors. Starting with the Chicago School, there has been an advocacy for environmental behavior studies to delve into real-world environments [8]. This study integrates traditional and modern approaches, combining traditional environmental behavior research methods with modern technology. By analyzing courtyard landscaping techniques, spatial prototypes, spatial cognition, and the characteristics of eye-tracking experiments, the study ultimately adopts three methods: literature analysis, subjective evaluation, and virtual eye-tracking experiments.

4. Study of Courtyard Space Visual Experience

4.1. Experimental Strategy

4.1.1. Experimental Preparation and Participants

This experiment selects an independent residence, "Kong House," as the main building. As shown in Fig.1, the residence incorporates the "courtyard" concept of traditional Huizhou dwellings, with a courtyard as the core for functional layout and spatial design. The house includes three courtyards of different sizes and functions, classified as comprehensive courtyard, landscape courtyard, and functional courtyard. For this study, the sketchup electronic rendering model of "Kong House" is chosen as the research object. Specific viewpoints are selected to collect eye-tracking data of individuals in the courtyard space. 10 participants were invited from Hefei University of Technology, including 4 male and 6 female participants.

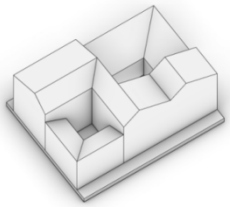

Figure 1: Axonometric drawing of Kong House

4.1.2. Viewpoint Selection

On the horizontal plane, the optimal visual field for humans is within a 60-degree angle, and observing objects within a 30-degree angle provides the highest clarity. The maximum observation range is 120 degrees. Fig.2 shows the five viewpoints selected on the first floor, with the pool (under the stairwell) and the restaurant obtaining the best view of the courtyard A, and the tea room and living room having the optimal view of the external tree well B. However, the entrance is relatively enclosed, making it difficult to achieve good landscape conditions and visual interest.

On the vertical visual field, calculated at a height of 1.6m, the viewpoints are taken around the courtyard corridor in Fig.3. Within the optimal visual field of 30 degrees, the highest point that viewpoint A can see is 5m (1.6 + (2.9÷1.71*2)), but the high side window on the second floor makes it challenging for the second-floor amusement center to connect with the courtyard on the first floor. It can establish visual contact with the corridor on the opposite side of the first floor.

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Within the optimal visual field of viewpoint B, besides appreciating the eaves and roof structure, it can also see part of the sky outside the roof, creating the traditional "falling white" effect in Huizhou architecture and forming a rich hierarchical visual field.

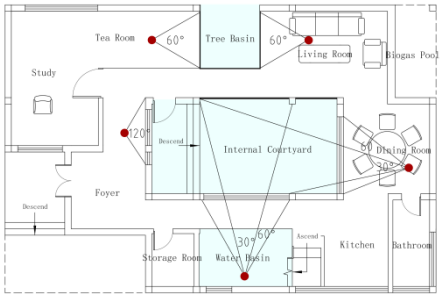


Figure 2: Horizontal viewpoint analysis diagram

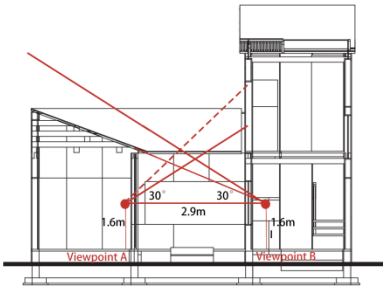


Figure 3: Vertical viewpoint analysis diagram

Based on the analysis of the viewpoints above, the author selected six viewpoints for the study, focusing on three courtyard scenes, as shown in Fig.4 and Fig.5.

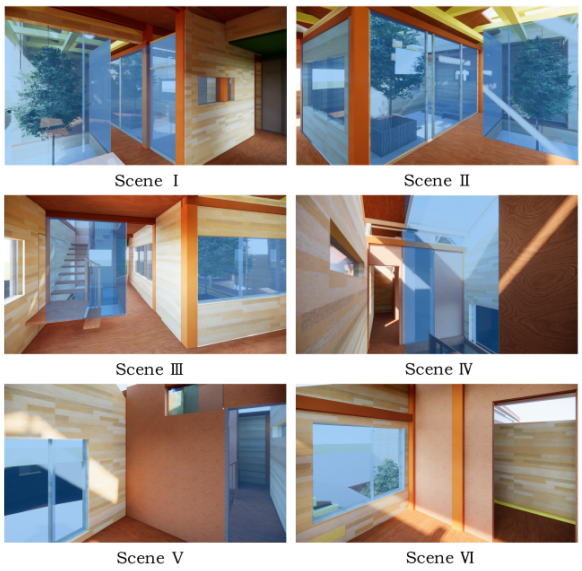
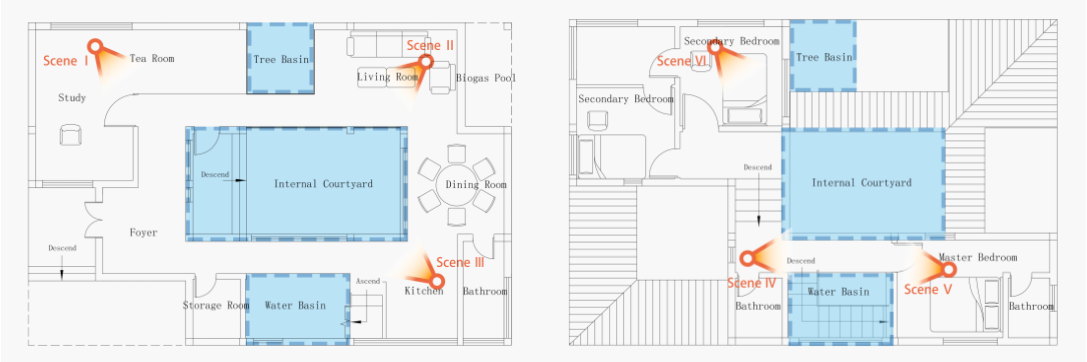


Figure 4: viewpoint selection



(a)

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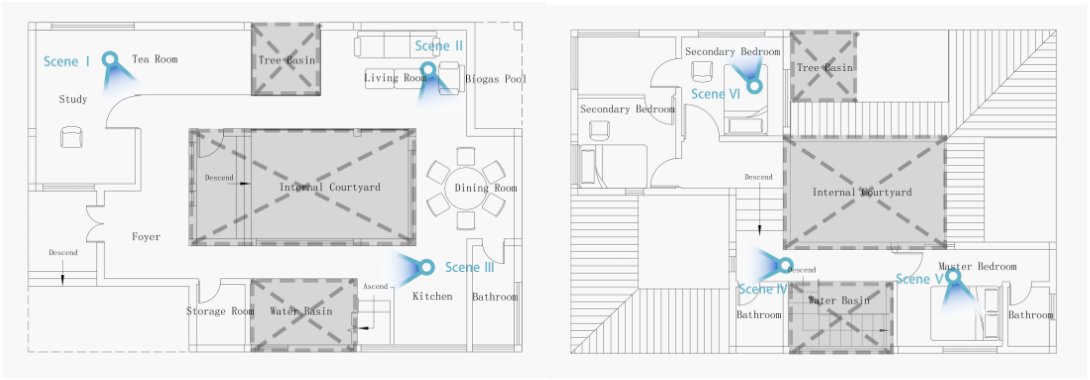

(b)

Figure 5: The viewpoint of the experimental group and the control group was selected. (a) The experimental group, (b) The control group.

4.1.3. Experimental Procedure

(1) After the subjects enter the laboratory, explain the experimental process and precautions to them. With the assistance of the instructor, adjust the equipment to ensure that they fully understand the experimental requirements.

(2) The subjects wear VR devices and perform automatic calibration according to the prompts of the equipment. The operator sets the scene in the SU software in advance to minimize data redundancy and errors caused by perspective switching. Adjust the perspective to the first scene.

(3) After successful calibration, the experiment begins. Six scenes featuring courtyard spaces are configured, with the courtyard space designated as the Areas of Interest (AOI), and control groups are established for each. In the same space and at the same viewpoint, the courtyard space is replaced with a solid wall. The subjects first observe scene 1 for 20 seconds, then immediately switch to the no-courtyard control group of scene 1 and continue observing for 20 seconds. Repeat this process for scene 2 and continue until all subjects have fully observed the 6 scenes and their control group scenes.

(4) After the experiment, export data such as AOI (Area of interest), fixation time and average eye movement count through virtual eye-tracking analysis software connected to the VR device for analysis. Fig.6 and Fig.7 show eye movement results.

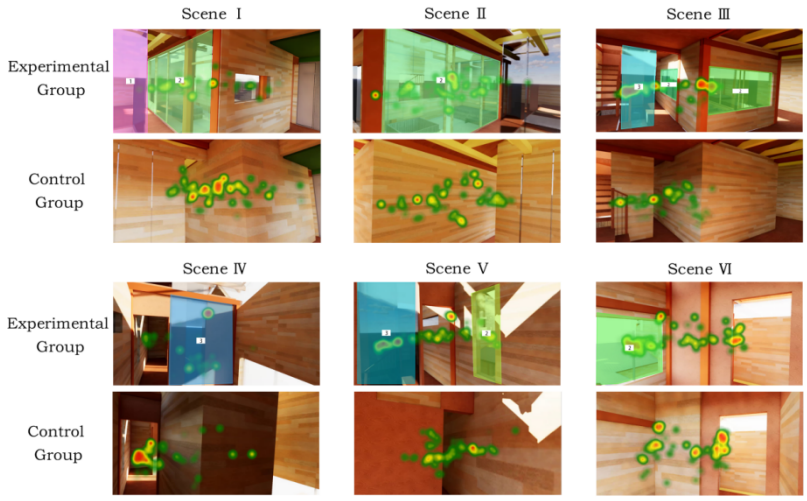

Figure 6: Each scene control eye movement experiment heat map

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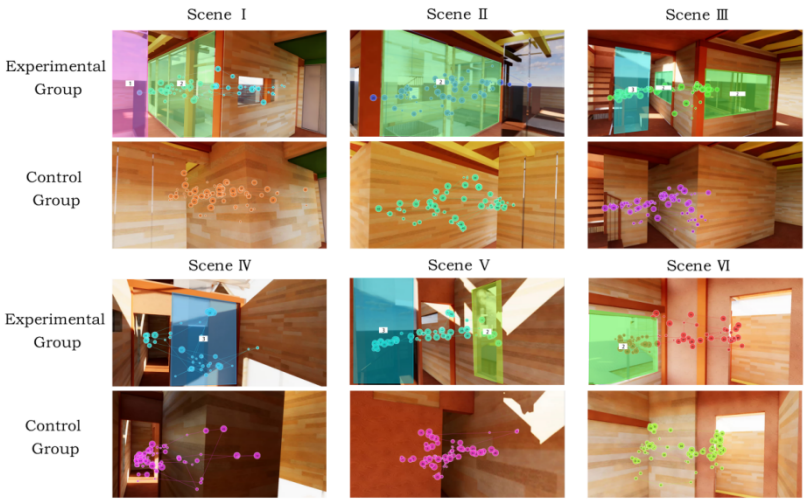

Figure 7: Eye movement trajectory diagram of each scene control eye movement experiment

4.2. Experimental Data Analysis

4.2.1. Average Saccade Frequency and Eye Movement Absolute Mean Diameter

Average saccade frequency (N/s) reflects the search behavior index of the subjects. The higher the frequency in unit time, the larger the search volume, indicating that the features of the image are less distinct. A larger eye movement mean diameter (px) indicates more distinct image features [9]. Based on the analysis of average saccade frequency and eye movement absolute mean diameter shown in Fig.8, the following two conclusions are drawn: 1). In general, the eye movement mean absolute diameter of subjects in spaces with courtyards (experimental group) is higher than that in spaces without courtyards (control group), indicating that the features of spaces with courtyards are more distinct, and the range of information acquisition is larger. The experimental group also has a lower average saccade frequency than the control group, indicating a smaller required search volume. This suggests that spaces without courtyards appear more unfocused and less distinctive in features. 2). In specific scenes, there is a significant difference in eye movement mean diameter between the experimental and control groups in scenes 2 and 4; the experimental and control groups have small differences in both data for scenes 5 and 6. Combined with visual analysis, scenes 2 and 4 have relatively simple elements, with the center of the field of view being one courtyard; scenes 5 and 6 have more complex elements, with two courtyards or additional variables such as scenic windows and high windows, which to some extent interfere with the effectiveness of the experiment.

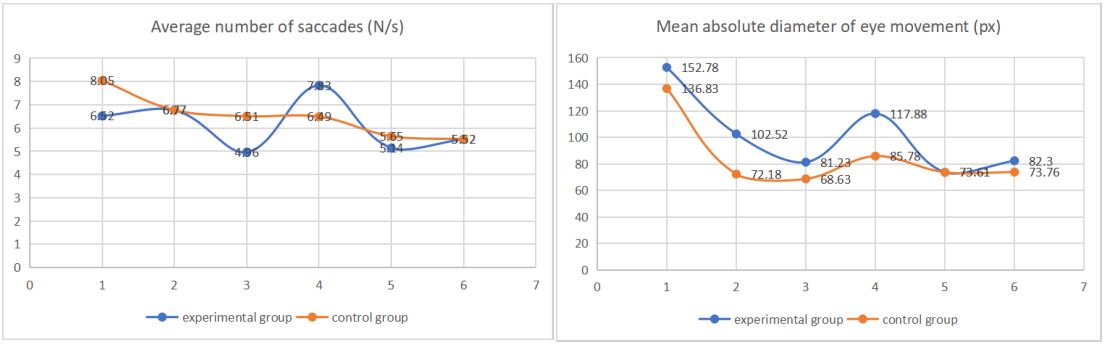

Figure 8: Figure of average saccade times and average diameter of eye movement

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4.2.2. Average Fixation Duration

Average fixation duration (ms) is the average duration of all selected fixations in the experiment. The longer the average fixation duration for each fixation point, the more effort the subjects put into recognizing the image. Based on the analysis of the average fixation duration shown in Fig.9, the following conclusions can be drawn: It is easy to see from the bar chart that in the experimental group with courtyard spaces (records with odd numbers), people's average fixation duration is generally longer than that in the control group without courtyard spaces (records with even numbers). This means that subjects need to put more effort into recognizing the presence of courtyard spaces in their field of vision. The more complex and rich in hierarchy the perceived space, the more information needs to be obtained and processed, and therefore, the required fixation duration is often longer. Therefore, this result also indicates that courtyard spaces can effectively enrich spatial hierarchy and landscape effects, making spatial features more prominent.

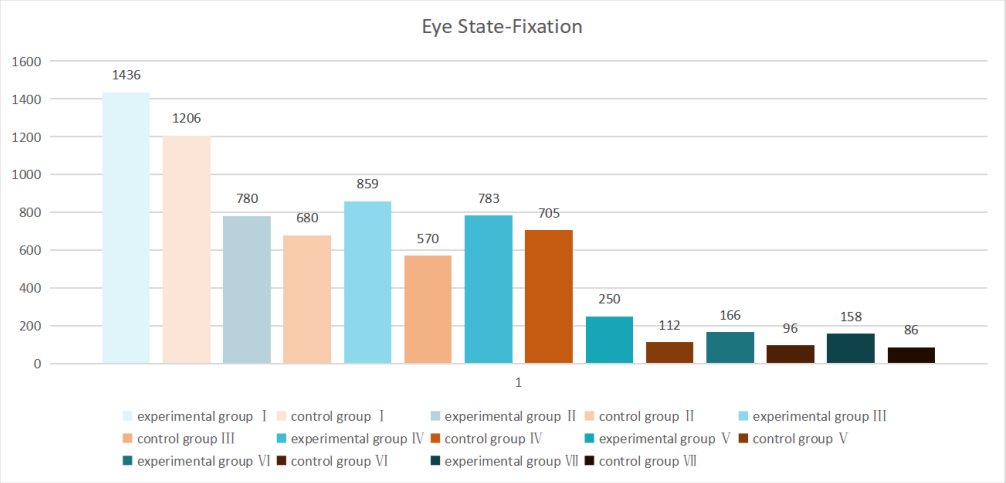

Figure 9: average fixation time

4.2.3. AOI Analysis

Area of interest (AOI) is a specific area in visual data with defined significance. Research has explored the connection between image data and AOIs, developing predictive models based on visual attention points. Numerous visual assessment methods identify key factors in static perceptual image quality considering human visual systems [10].

In the experimental group, the author delineated the area occupied by the courtyard space through AOI, and statistics were conducted on the proportion of fixation times in this area, total fixation time, total visit duration, and the time spent on the first attention to the AOI area. we can see from Fig.10 that: In the experimental group with courtyard spaces, the proportion of fixation times in the AOI courtyard area reached over 50%, and the first attention time to the AOI area was relatively short, quickly attracting people's attention. This indicates that in a certain field of vision, courtyard spaces are more visually attractive compared to other architectural elements.

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Figure 10: AOI Analysis Chart

By synthesizing multiple experimental data, it can be observed that the inclusion of courtyard spaces in traditional residences effectively enriches spatial visual hierarchy, adds spatial interest, attracts attention, and enhances the quality and recognizability of space. The experimental data also quantitatively validate the scientific nature of the design theory of courtyard spaces in traditional residences.

5. Visual Experience Differences in Different Types of Courtyard Spaces

5.1. Questionnaire Experiment Design

Courtyard spaces come in many types. In this paper, by selecting three different types of courtyard spaces within the "Kong House" as the basic spaces and using questionnaire analysis, the subjects' subjective and direct judgments on their spatial qualities and visual experiences are collected. The initial analysis aims to explore the visual experience differences between comprehensive courtyard spaces, landscape courtyard spaces, and functional courtyard spaces. Through a longitudinal analysis of the previous virtual eye-tracking experiments, further exploration of the visual experience differences is conducted. Questionnaire experiments are difficult to capture eye fixation duration and sequence, making it challenging to analyze and evaluate directly. Therefore, information on subjects' experiential feelings is collected, analyzing their attention and choices regarding space, landscape, color, light, and shadow in five aspects.

The experiment selected three courtyard spaces in the "Kong House": Courtyard Space 1 illustrated in Fig.11(Comprehensive Skywell), Courtyard Space 2 illustrated in Fig.12(Landscape Skywell), and Courtyard Space 3 shown in Fig.13(Functional Skywell).

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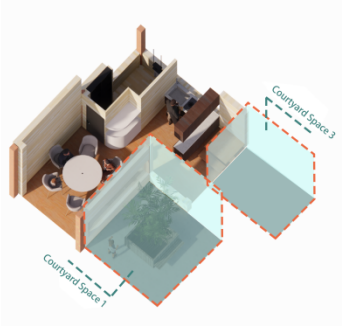

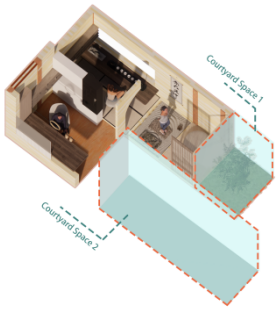

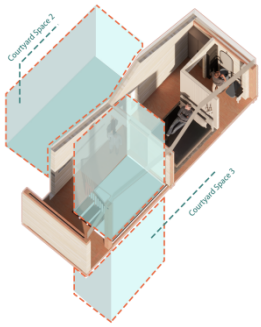

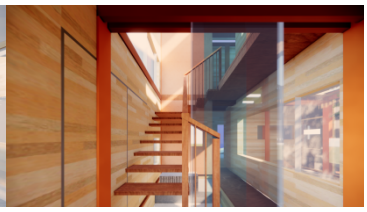

Figure 11: Comprehensive Skywell Figure 12.Landscape Skywell Figure 13.Functional Skywell

5.2. Questionnaire Experiment Data Analysis

5.2.1. Differences and Elements in Visual Experiential Perception

Courtyard spaces have numerous visual experience elements. Different forms of the top interface lead to distinct light and shadow effects; the transparency of the enclosing interface affects the smoothness of the field of view; different landscape designs bring different psychological feelings. Table 1 provides a subjective evaluation of three types of courtyard spaces by subjects, along with the attraction of spatial environmental elements to vision. Through horizontal data analysis, comprehensive courtyards generally give a comfortable feeling, representing a more ideal psychological space. The proportion of people feeling comfortable in landscape courtyards is about 50%, while approximately 30.77% feel suppressed and anxious in functional courtyards, indicating poorer visual and perceptual experiences. Through longitudinal data analysis in the order of "Comprehensive Courtyard—Landscape Courtyard—Functional Courtyard," the sense of suppression gradually increases, and comfort gradually decreases.

Fig.14, through single-factor data analysis, shows that in comprehensive courtyards, the openness of the space is the main factor attracting vision; in landscape courtyards, the light and shadow created by the spatial landscape are the main factors attracting vision; in functional courtyards, the light and shadow of natural light are also the main factors attracting vision.

Fig.15, through cross-analysis of the data, indicates that in terms of space openness, about 62% of people believe that the space in comprehensive courtyards is more open, while functional courtyards and landscape courtyards are relatively enclosed. In terms of landscape factors, about 50% of people believe that the landscape environment of comprehensive courtyards is better and more attractive to vision. In terms of light and shadow factors, it can be seen that the visual effect of light and shadow in comprehensive courtyards is relatively poor.

Table 1: The experience difference of different types of skywells

	Depression and anxiety	Lack of experience	Comfort and pleasure
Comprehensive patio	3.85%	38.46%	61.54%
Landscape patio	7.69%	46.15%	50%
Functional patio	30.77%	42.31%	38.46%

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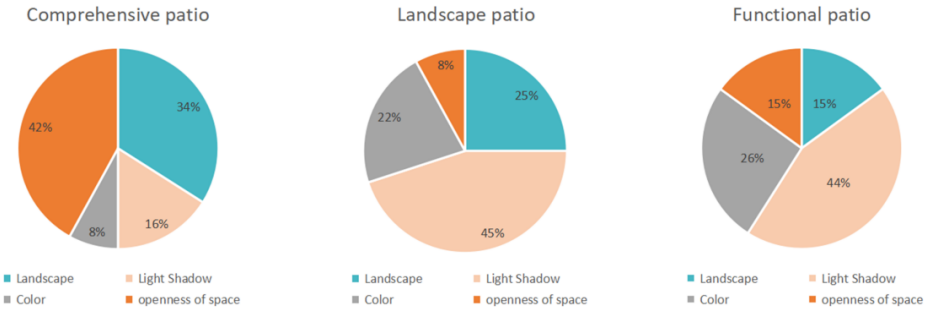

Figure 14: The proportion of visual elements attracted by different skywells spaces

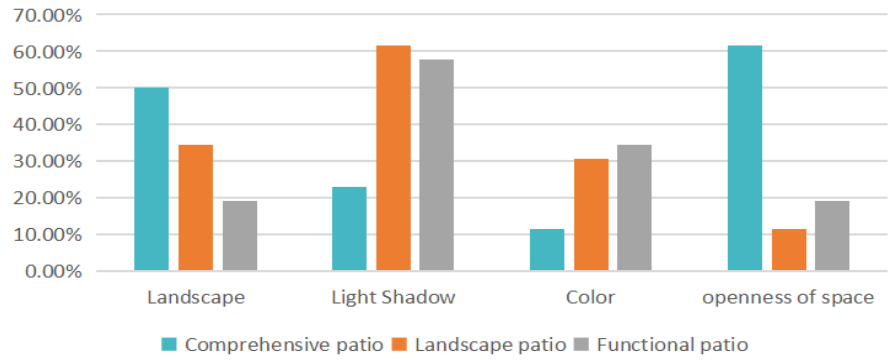

Figure 15: The proportion of different skywells spaces under the same environmental factors,

5.2.2. Environmental Differences Elicit Various Behavioral Responses

The environment, concerning a central element, exerts influences on it. Regarding humans, the environment affects human behavior. As previously discussed, the interaction between humans and the environment involves environmental elements, which, through visual and perceptual experiences, stimulate observers. The complexity and mystery of environmental elements increase the observer's desire to explore the environment. The questionnaire design aimed to collect subjects' experiences of the environment and subsequently gathered information about subjects' potential behaviors induced by environmental stimuli.

Based on Fig.16, when exposed to the stimulating environment of a comprehensive courtyard space, subjects are more inclined to "take another look" or "enter the space to rest and chat." Data from Figure 2 indicates that most subjects in the landscape courtyard space desire to "take another look," but a majority of subjects also choose to "leave." Figure 3 data shows that most subjects in the functional courtyard space choose to "leave." Analyzing the chart data reveals that as the spaciousness of the space and the landscape environment change, the proportion of choosing to "leave" gradually increases, while the proportion of choosing to "stay" decreases.

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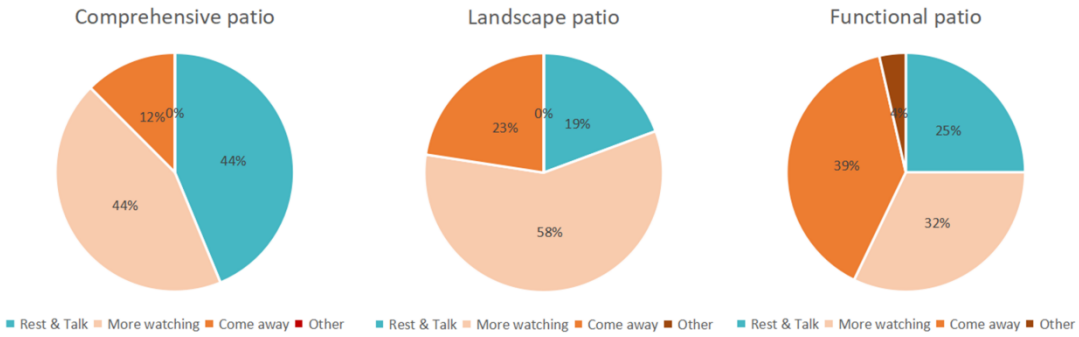

Figure 16: The proportion of behaviors that different types of skywells may guide

5.3. Longitudinal Analysis of Virtual Eye-tracking Experiment Data

As shown in Fig.10, in the eye-tracking experiment's experimental group, Scenes 1 and 2 represent the perspectives of comprehensive courtyard space and landscape courtyard space, while Scenes 3 and 4 represent the perspectives of functional courtyard space. According to the data in the figure below, the AOI fixation count, AOI total fixation duration, and AOI total visit duration ratios of Scenes 1 and 2 are much higher than those of Scenes 3 and 4. A comparison indicates that comprehensive courtyard space and landscape courtyard space are more attractive and visually satisfying than functional courtyard space.

Through the questionnaire and eye-tracking experiment, we found that different types of courtyard spaces produce different visual experiences for individuals due to the complexity of their environments. The more complex the courtyard space environment, the stronger the stimulation on individuals, leading to a more intense desire for exploration.

6. Conclusion

This paper explores and validates the impact of courtyard spaces on enriching spatial visual effects from the perspective of users' visual behavior and perception. Utilizing research methods such as virtual eye-tracking experiments and literature collection analysis, the visual experiences of three courtyard spaces in the "Kong House" are examined and verified. By inviting participants to wear VR devices and enter virtual spaces, the eye-tracking equipment is employed to analyze various data points from participants in spaces with and without courtyards. Through a comparative analysis approach, the study reveals that incorporating courtyard spaces in traditional residences effectively enhances spatial visual hierarchy, adds visual interest, captures attention, and elevates overall spatial quality and recognizability. The experiment's quantified data validates the scientific principles of courtyard design in traditional dwellings.

The survey experiment, designed to collect data, illustrates that variations in courtyard space types result in differences in visual experiential effects. The analysis focuses on participants' attention, choices, and potential behaviors in terms of space, landscape, color, light, and shadow. The findings suggest that the visual experiences of different courtyard spaces vary due to their environmental complexity. The more complex the courtyard space environment, the stronger the stimuli it provides to individuals, leading to a heightened desire for exploration.

Virtual eye-tracking experiments and quantitative analyses are expected to further deepen their application in real-site studies, providing more comprehensive data on user visual attention and perceptual patterns for design purposes. Research based on virtual eye-tracking devices holds promise in becoming a scientific and practical guide for architectural design.

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This study has some limitations. The participants consisted only of university students with similar ages, lacking diversity in the sample. In future research, a more in-depth exploration of the correlation between visual perception and psychological perception will be conducted, providing additional strategies and references for practical applications.

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