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Patio Design Optimization for Huizhou Traditional Dwellings Aimed at Daylighting Performance Improvements

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Abstract: Hui-style architecture is a mature architectural school in the late period of ancient Chinese society with distinct regional cultural characteristics. Especially as the most direct carrier of Huizhou people's living culture, Hui-style architecture is the witness of ancient Huizhou society, history, and culture. However, with the continuous development of society, residents gradually put forward higher requirements for the living environment. In this paper, the indoor light environment of Huizhou dwellings is measured and found to have problems such as poor indoor light environment and low light quality. In order to improve the indoor lighting quality, this study extracts the key design parameters (window edge height, window width, patio length, and patio width) that affect the indoor lighting quality through field research and literature analysis, and then uses Honeybee to carry out multi-factor orthogonal experiments and single factor quantitative comparative analyses on the key design parameters to determine the degree of influence. The results show that reducing the window edge height can improve the lighting effect near the window, and increasing the window width and patio width can improve the overall lighting quality of the room, thus providing a reference for optimizing the lighting effect of Huizhou traditional dwellings.

Keywords: Huizhou dwellings; indoor light environment; patio space form

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1. Introduction

The traditional folk house is folk, native, and rich in historical and cultural value and local characteristic value architecture [1]. In China, it is mainly divided into two types: enclosed residential buildings and sheltered open residential buildings. As an important representative of the hall and well model of sheltered open residential buildings [2], Huizhou dwellings are one of the most representative traditional residential buildings in China, which are mainly distributed in southern Anhui Province. Although Huizhou dwellings have evolved into today's space form in the flood of history, with the continuous development of economy and society, residents gradually put forward higher requirements for living spaces. Due to the mutual occlusion of their spatial layout and structure, Huizhou dwellings have always had poor indoor light environment, low light quality, and other natural lighting problems that need to be improved. A good indoor lighting environment is the basis for people's work, study, and life. It can improve people's work efficiency and quality of life, protect people's physical and mental health, and enhance people's sense of happiness [3]. Therefore, improving the indoor lighting quality of Huizhou dwellings is an important part of the development process of Huizhou dwellings.

In recent years, Daylight Factor (DF), Spatial Daylight Autonomy (sDA), and Useful Daylight Illumination (UDI) as dynamic lighting indicators have been widely recognized in indoor lighting evaluation [4]. DF is the first dynamic indicator to evaluate indoor lighting. It refers to the percentage of time that the minimum illuminance requirements can be reached during the working hours of the whole year by relying on natural lighting alone [5]. It is a conventional static lighting evaluation indicator used in architectural design in many countries [6]. In China, the evaluation standard for daylighting the design of residential buildings [7] is also based on DF and indoor natural illuminance standard values. However, there are some limitations in using DF as an evaluation tool, which is not applicable to weather conditions other than overcast days [8]. sDA is recommended by IES. sDA300/50% is the percentage of the calculation points in the horizontal direction of space. An amount of 50% of the time (10 h a day) in a year can reach 300 lx under natural light [9]. UDI is proposed by Nabil and Mardaljevic [10], which is used to evaluate the time proportion of natural lighting at each point in a space within the acceptable range of the human eye. These three dynamic evaluation indexes are used to analyze spatial natural lighting distribution. For building natural lighting, there is also a need to prevent glare. IESNA [11] defines glare as "the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility." The two main indicators used to evaluate glare are the Daylight Glare Index (DGI) and Daylight Glare Probability (DGP) [12].

Many scholars have studied and analyzed the indoor light environment of Huizhou dwellings before. Rao Yong [13] measured the illumination, temperature, humidity, and other physical environments of the three Huizhou dwellings, namely Youqing House, He Wenxue House, and Tongde House, and used Ecotect to optimize the analysis of the three traditional residences from the size of the daylight opening, size, and size of the external window, in order to increase the lighting coefficient in the room by 8.96% at most. Duan Zhongcheng [14] and others measured the reflective coefficient and illuminance value of traditional building materials on the spot and converted them into lighting coefficients. They mainly studied and analyzed the lighting of Huizhou traditional dwellings with the light well index (WI) and the reflection coefficient of the enclosure surface. They concluded that the larger the WI the worse the light environment of the patio is. They pointed out that the reflection coefficient can be changed by brushing the wall to improve the lighting. Li Yanqing [15], on the basis of maintaining traditional dwellings, summarized and sorted modern and traditional lighting technologies in order to form a lighting optimization system for Huizhou dwellings. On the basis of the measured data of Youqing House and the roof tiles, he increased the area of windows and optimized the indoor lighting environment by using sun shading skylights, daylighting panels, and light pipes. Liu Tianyu [16] divided the form elements of the compact living environment into spatial opening, window opening, and interface features. Designed control tests on form elements such as room depth, balcony form, window scale, window sill height, and window layout, respectively, to determine the influence of each element on indoor light comfort of miniature living space, studied and analyzed the correlation degree between each form element and indoor light comfort of living space, and proposed the direction of optimization of various form elements. Iason Bournas [17] and colleagues used an observer-based environmental assessment (OBEA) to investigate the lighting conditions inside. In order to measure the perceived brightness and distribution of daylight, the OBEA used self-administered questionnaires based on bipolar semantic scales. The results of the study, which looked at the degree of correlation between the seven parameters of the walls, windows, room spaces, and room daylight conditions in residential buildings, came to the conclusion that the window-related characteristics had a stronger correlation with perceived brightness. In summary, there is a lack of relevant research on the lighting performance of Huizhou dwellings, and most of them focus on the actual research and optimization measures for individual buildings, but the optimization measures are not necessarily suitable for all buildings of this type and there is a lack of extraction and summary of the architectural forms related to the lighting performance of Huizhou dwellings, which propose more universal lighting measures to improve the lighting performance of Huizhou dwellings.

As a result, this study examines Huizhou dwellings' natural daylight in relation to their spatial shape. By analyzing and comparing the field survey data, this study selects the patio space as an important design parameter for the lighting analysis of Huizhou dwellings. The courtyard is one of the representative elements of Huizhou dwellings, and also the core of the spatial structure of Huizhou dwellings. The patio has an important influence on the indoor ventilation and indoor thermal and humid environment. However, some Huizhou dwellings have good lighting effects, while some halls have good lighting effects and some wing rooms have poor lighting effects [18]. This is because Huizhou is hot and humid in summer. In order to tolerate the indoor thermal environment, sun shading should be given priority in the design, supplemented by natural ventilation [19]. Therefore, in addition to the semi-open halls, some wing rooms will suffer from a serious shortage of lighting. In the spatial pattern of typical Huizhou dwellings, it is of great significance to test and identify the real key design parameters in the patio space to obtain better dynamic lighting performance.

This paper selects Huizhou dwellings as the research object and goal, aiming to use the courtyard space of Huizhou dwellings to provide natural lighting, to improve the indoor light environment by reasonably changing the design parameters of windows. Based on the courtyard space of Huizhou traditional dwellings, the characteristics of traditional courtyard space are summarized and analyzed in combination with the field survey data. On the basis of extracting the basic courtyard space prototype and combining the common design parameters of windows, the key design parameters (window edge height, window width, courtyard length, and courtyard width) of Huizhou traditional dwellings are proposed for a multi-factor orthogonal experiment and a single factor analysis experiment. With the help of the Honeybee plug-in, based on the Radiance engine, the quantitative analysis of the impact of different elements of design parameters on the light environment of indoor space was carried out, aiming to provide a lighting optimization strategy that not only protects the regional space characteristics of Huizhou dwellings, but also conforms to modern scientific norms for the reconstruction and new construction of residential buildings. The framework of this study is shown in Figure 1.

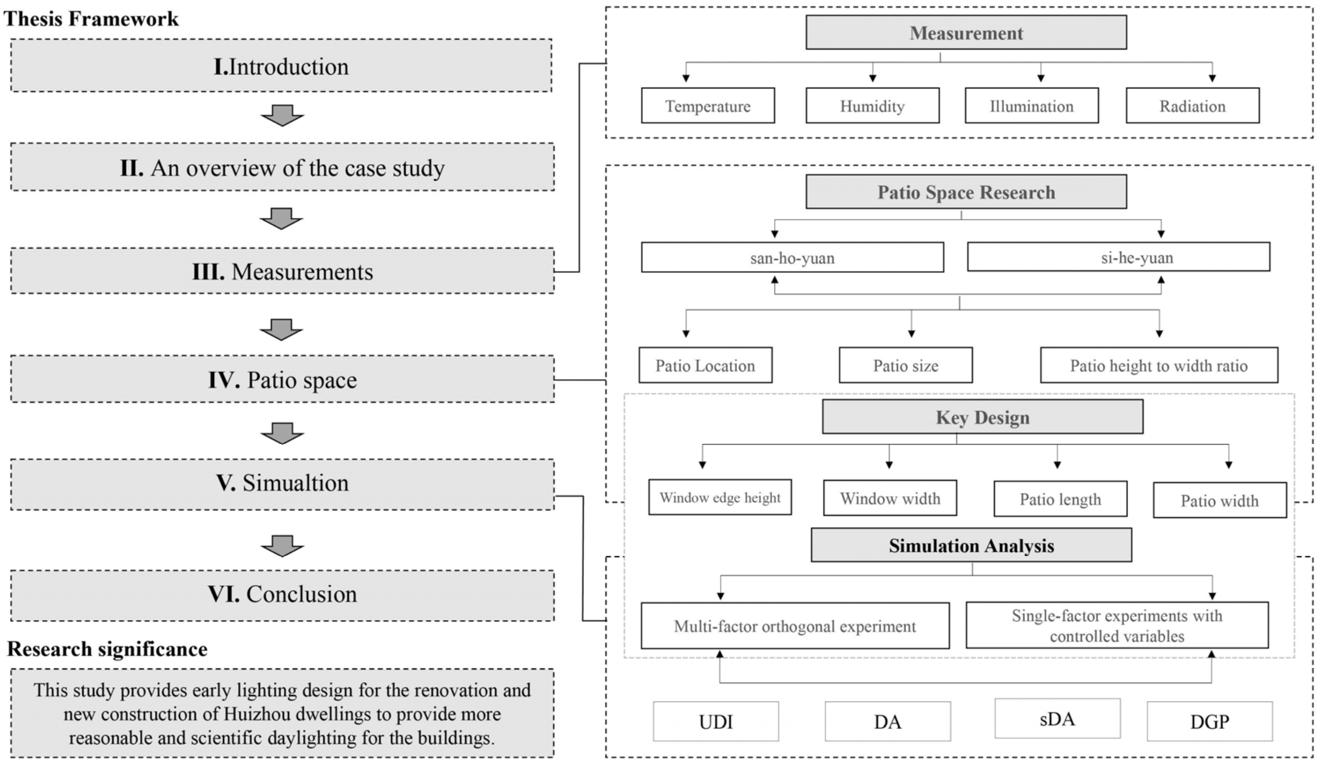


Figure 1. Research framework.

2. An Overview of the Case Study

2.1. Climatic Context

Huizhou has a subtropical monsoon humid climate, characterized by a year-round humid climate, abundant rainfall, four distinct seasons, hot summers, and cold winters. The average annual precipitation is 1800~2000 mm, mainly in spring and summer (from May to August). The rainy season is from the middle of June to the first ten days of July. During this period, the area has rainy days, high temperatures, and humidity. According to the meteorological data collected from the Chinese Standard Weather Data of the Tunxi Meteorological Station [20], the annual average temperature here is 16.3 °C, the monthly average temperature in summer (from June to August) is 26 °C, the monthly average relative humidity is 79.7%, the average temperature in winter (from December to January) is 5.7 °C, and the monthly average relative humidity is 78.7%, as shown in Figure 2. The Huizhou region belongs to the fourth category in the light climate division, and the light energy resources are general. There are more sunshine hours in summer and throughout the day, and less sunshine hours in winter. The average sunshine hours in Huizhou are 1732–1970 h, the average sunshine percentage is 42%, and the average annual solar radiation is 110 kcal/cm^3, lower than the average total solar radiation in the Anhui Province.

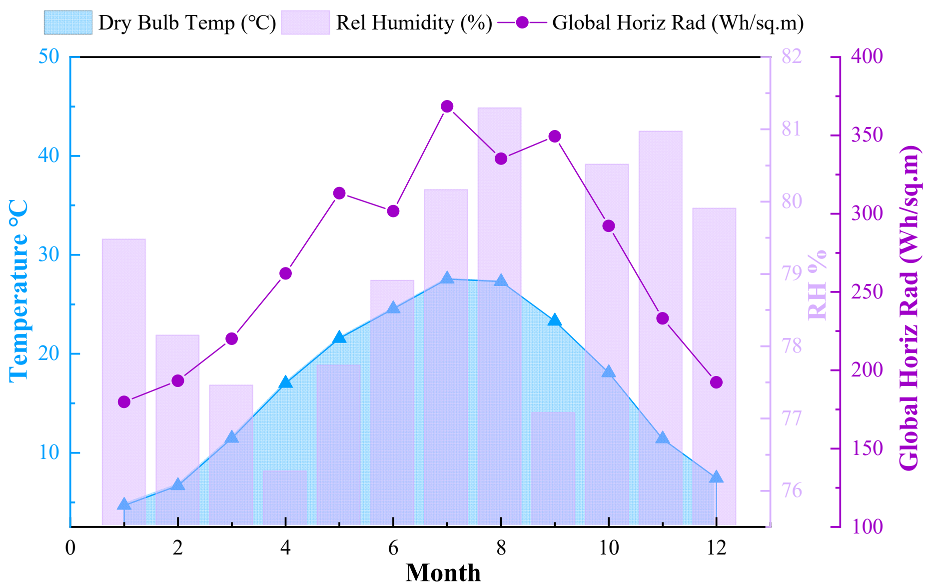


Figure 2. Climate Data of Temperature, Relative Humidity, and Solar Radiation in Tunxi, Huizhou.

2.2. Case Studies' Presentation

2.2.1. Functional Space

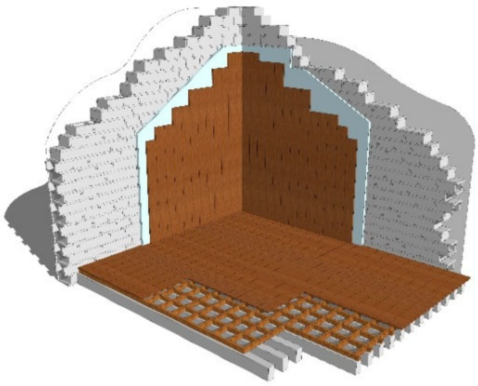
A traditional folk house with typical characteristics of Huizhou dwellings in the Qing Dynasty was selected, which is located in Xidi Village, Xidi Town, Yixian County, Huangshan City. The folk house faces the southwest and enters the courtyard in the shape of "日". As shown in Figure 3, except that the main house of the first courtyard is two floors, the eaves gallery and the front hall (now changed to the kitchen) are both on the first floor, and all buildings in the second courtyard are on the second floor, and the building height increases from south to north as a whole. Every time the building enters the courtyard, there is a gate that opens to the streets and alleys. The gate is decorated with a door cover and a gate tower. In terms of architectural function, the first floor is the living area, the dining room is connected with the kitchen, the wing rooms are all bedrooms, and the two halls are living rooms, which retain the decorative style of the old house. When there are many people, they will eat at a round table. The eaves gallery on one side of the street is used for transportation, and the other side is used for storage. As there are only four permanent residents, the rooms on the first floor are enough for use, and the second floor is all used for storage, with some large farm tools, wood, grain, etc. Figure 3 shows the functional space of the house.

Figure 3. Functional space diagram of the test house.

2.2.2. Construction Characteristics and Thermal Properties

Huizhou dwellings combine two types of wood structures into one building, post and lintel construction and column and tie construction. The combination of the two can save materials and increase the stability of the structure. The surrounding walls are not load-bearing and are fixed on the wooden frame with iron nails. The envelope structure of Huizhou dwellings can be divided into two parts, the supporting system is timber framed, and the exterior wall is a masonry structure. The outer wall is an empty bucket brick wall with a thickness of 300 mm, built with grey bricks, and the load-bearing structure is column and tie construction. The external wall is built with hollow bricks, with two layers of grey bricks inside and outside, filled with gravel and soil in the middle, and painted with lime on the surface with few windows. The size of grey brick is 200 mm × 150 mm × 30 mm, the brick size of two flat sides and single wall is 250 mm × 150 mm × 60 mm, the thickness of all walls except single wall is 300 mm, the thickness of single wall is 150 mm, and the thickness of chalk plaster on all wall surfaces is 5 mm. The internal partition walls, ceilings, floors, doors, and windows are all made of wood. The patio and corridor are paved with bluestone. The ground of the first-floor hall is paved with tabia. The floor of the wing room and eaves gallery is paved with boards. See Table 1 for the structure of the building envelope.

Table 1. Materials and characteristic parameters of enclosure structure.



Envelope	Materials	Thickness (m)
External wall	White lime	0.005
	Clay brick	0.3
	Yellow mud	-
	Air gap	0.05
	Board	0.05
Internal wall	Board	0.05
Low floors	Air gap	0.15
	Board	0.05
Intermediate floors	Board	0.05
Roof	Tile	0.0167
	Stucco	0.02
	Sheathing	0.02

The wood floor of the bottom wing room is built on the wood joist with a distance of about 15 cm from the ground, which is conducive to ventilation and moisture resistance. The floor of the hall shall be paved with polished concrete or square bricks, and the wing room shall be paved with wooden boards. Wooden grilles were placed under the floor. Some will be paved with bricks above for fire prevention, and the patio floor shall be paved with bluestone slabs.

3. In Situ Measurements

3.1. The Measurement's Protocol

In order to study the influence of various design parameters on the indoor lighting environment of Huizhou traditional dwellings in winter and summer, a series of tests were carried out. The winter test was conducted from 11:00 on 24 December to 11:00 on 27 December, and the summer test was conducted from 9 to 11 July. The field test includes the solar radiation intensity, temperature and relative humidity of indoor/outdoor air, and illuminance. Figure 4 shows the measuring points arrangement. Table 2 shows the instruments for all corresponding parameters.

Table 2. Measured parameters and instruments.

Measured Parameters	Instrument	Precision	Notes
Temperature and relative humidity of indoor/ outdoor air	TR-72UI auto-logger thermometer	±0.2 °C	Auto acquisition per 10 min
Solar radiation	TBD-1 scattering radiometer TBQ-2 total radiometer	7~14 μV/W·m^{-2}	Manual acquisition per 30 min
Illuminance	TES-1332A illuminometer	±3% rdg ±0.5% fs	Manual acquisition per 30 min

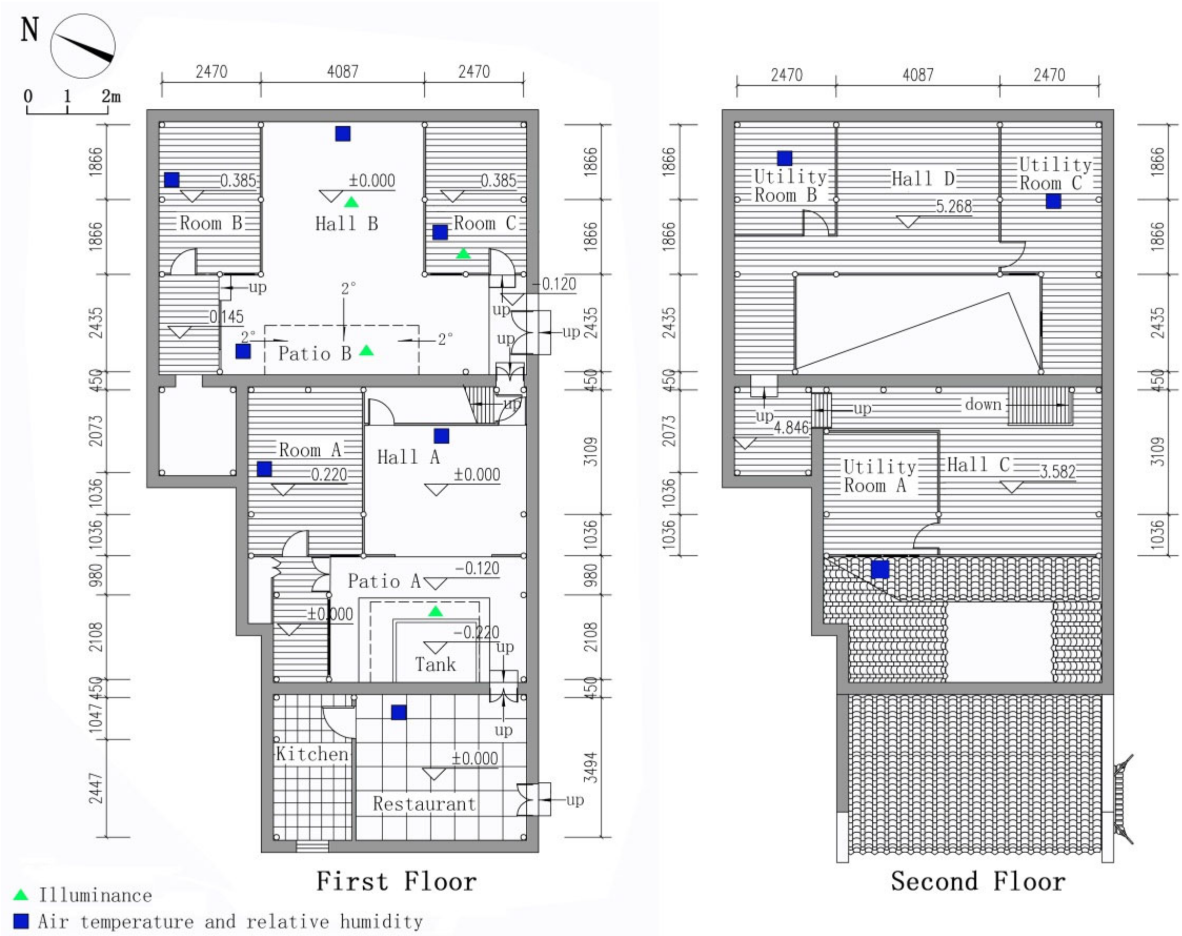


Figure 4. Plan view of test house showing the monitoring points.

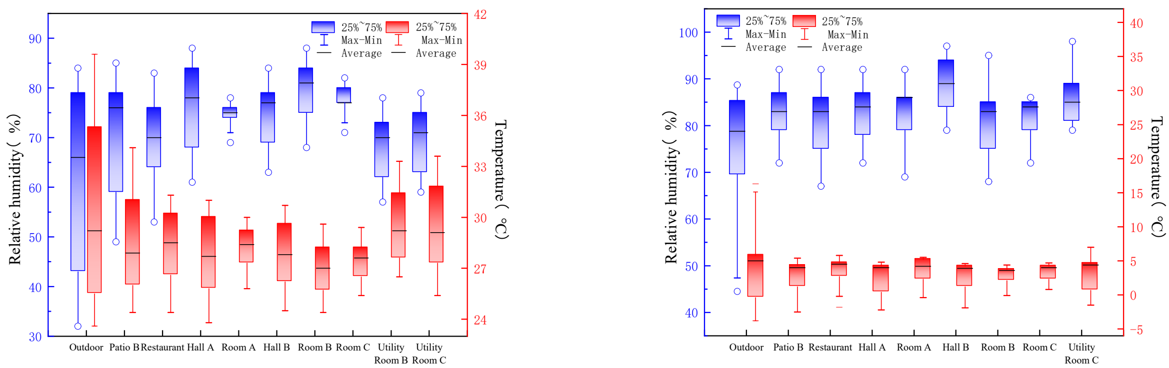
3.2. The Monitoring Data and Analyze

3.2.1. Air Temperature and Relative Humidity

The data period was from 16:30 on 9 July to 16:30 on 11 July in summer, and the test interval was 10 min. Figure 5a shows the range, maximum value, minimum value, average value, and comparison of indoor and outdoor air temperature and relative humidity. The outdoor air temperature fluctuated the most with a daily range of 16 °C, followed by Patio B, Room C, and Room B, with daily ranges of 9.7 °C, 8.2 °C, and 6.8 °C. Then, there was Hall A, the dining room, and Hall B, with daily ranges of 7.2 °C, 6.9 °C, and 6.2 °C, respectively. The smallest daily range was in the three wing rooms, of which Room A was 4.2 °C, Room B was 5.2 °C, and Room C was 4 °C. The maximum outdoor air temperature can reach 39.6 °C, while the maximum indoor air temperature was 33.6 °C and 33.3 °C, respectively, in two rooms on the second floor. The indoor minimum temperature was concentrated in the range of 23.8 °C~26.5 °C, while the outdoor minimum temperature was 23.6 °C. The average outdoor air temperature was 30.3 °C, while the average indoor temperature of the second-floor room was 29.4 °C and 29.5 °C, and the average temperature of the first-floor room was between 26.9 °C and 28.5 °C.

Data analysis was conducted for 48 consecutive hours from 17:00 on 24 December to 17:00 on 26 December, with an interval of 10 min. Figure 5b shows the range, maximum value, minimum value, average value, and comparison of indoor and outdoor air temperature and relative humidity. The outdoor air temperature ranges from −3.8 °C to 16.3 °C, with an average of 4.2 °C. The maximum air temperature appears at 14:00 in the afternoon and the minimum at 6:00 in the morning. The temperature variation in each indoor room is similar, with the average value between 2.5 °C and 3.6 °C, which is lower than the average outdoor temperature. The maximum indoor temperature appeared in Room C on the second floor, which reached 7 °C at 16:00, followed by Patio B, the Restaurant and Room A, which appeared at 14:00, 18:00, and 7:00. The maximum temperature of Patio B was closely related to the solar radiation and air temperature; thus it was similar to the outdoor maximum temperature. The maximum temperature of the Restaurant was related to people's cooking and activities after meals, while the high temperature of the bedroom was related to people's sleeping time. The lowest indoor temperature occurred in Patio 2, Hall A, Hall B, and the Restaurant at around 8:00. Additionally, the lowest temperature in the three bedrooms was relatively high.

Figure 5a shows the range, maximum value, minimum value, average value, and comparison of indoor and outdoor relative humidity in summer. The variation range of outdoor air humidity was the largest (32~84%), followed by Patio B (49~85%), Room A (69~78%), and Room C (71~82%) on the first floor. This shows that the indoor air humidity change was small and relatively stable, and the air humidity change in first floor wing room was the smallest and most stable. The outdoor air average relative humidity was 61.6%, and the average humidity ranged from 68.5% to 79.3% in the rooms in the building. As can be seen, indoor and outdoor humidity was generally high, coupled with the air temperature, the outside in high temperature and humidity, while the indoor temperature was not high, but humidity was relatively high.



(**a**) (**b**)

Figure 5. Comparison of outdoor and indoor air temperatures and relative humidity: (**a**) Summer; (**b**) Winter.

Figure 5b shows the range, maximum value, minimum value, average value and comparison of indoor and outdoor relative humidity in winter. The outdoor air relative humidity ranges from 22.5% to 88.7%, with an average value of 75.4%. The maximum value appears at 10:50 and the minimum at 14:40. The maximum indoor air relative humidity ranges from 86% to 98%, the average ranges from 80.5% to 88.8%, and the minimum ranges from 67% to 79%.

3.2.2. Solar Radiation and Daylight

The test place was the Xidi village entrance square from 8:00 to 16:30 on 25 December. The total radiation quantity and scattered radiation quantity were directly measured by the instrument, and the direct radiation quantity was calculated by subtracting the total radiation quantity from the scattered radiation quantity. The test results are shown in Figure 6a. The figure shows the maximum solar radiation in a day occurs at 12:00, and the radiation amount is 559 W/m^2. The maximum radiation period is from 11:00 to 13:00, and the average daily radiation intensity is 345 W/m^2. The scattered radiation changes gently with time, accounting for 27.9% of the total radiation. Xidi Village under the Huangshan City (established in 1987, formerly known as Tunxi City) belongs to the area VI, which has high suitability, low demand, and a small temperature fluctuation, thus it is not recommended to use passive solar heating [8].

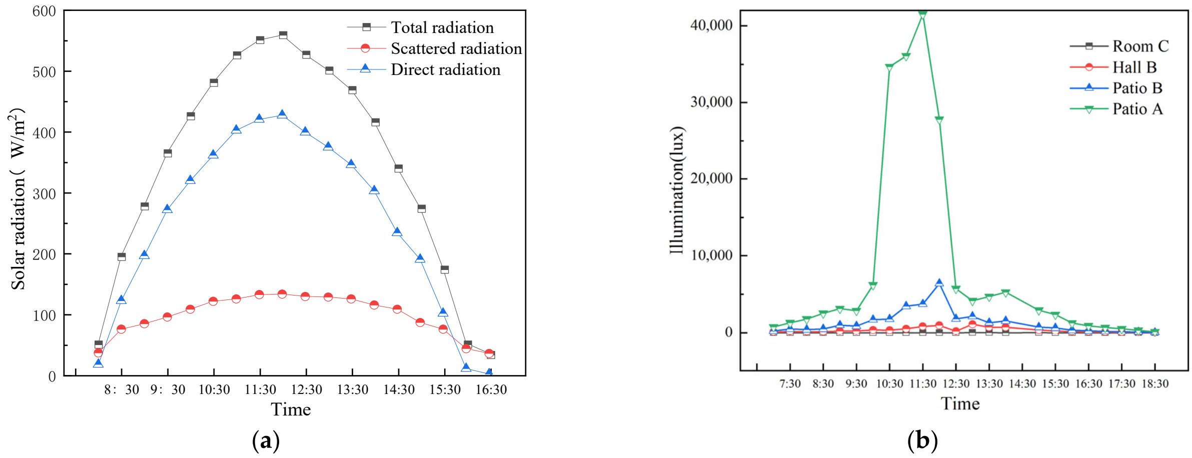


Figure 6. (**a**) Solar radiation in winter; (**b**) Illumination in summer.

The test time in summer was from 7:00 to 18:30. The illuminance values of Room C, Hall B, and Patio A and B were tested. The test results are shown in Figure 6b. The figure shows that Patio A has the highest illuminance value with a range of 116–41,500 lux, while bedroom C has the lowest illuminance value with a range of 0.1–30.2 lux. The illuminance peaks in the four spaces occurred between 10:30 and 14:00, with the hall and bedroom peaking about half an hour later than the patio space.

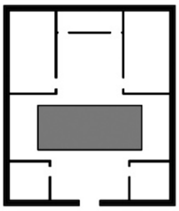
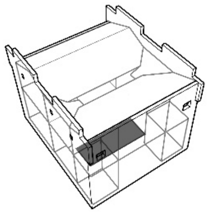
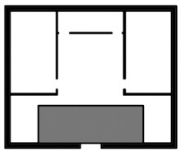
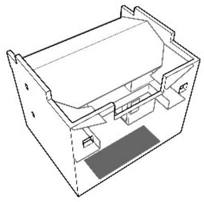
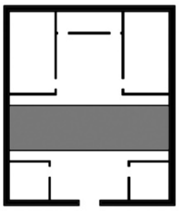
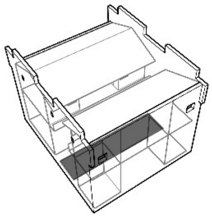
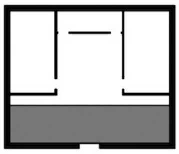
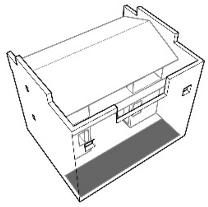
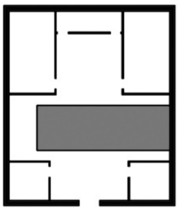
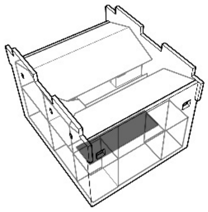
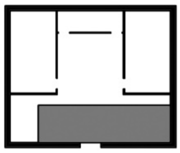
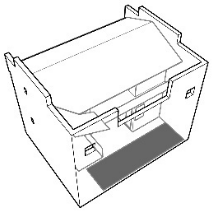
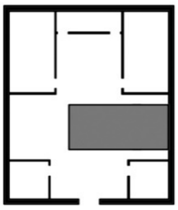
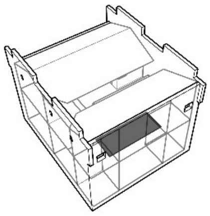
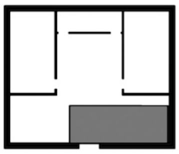
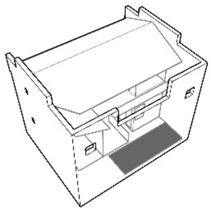
As shown in Figure 6b, the illuminance values of Patio A and Patio B are significantly higher than the hall and bedroom. As a part of the building space, the patio can obtain sufficient illuminance values, while the bedroom, as a neighboring building space in contact with the patio space, cannot obtain sufficient illumination. The difference of illuminance between patio and bedroom indicates that there are defects of natural lighting in the adjacent space of patio in Huizhou dwellings.

4. Patio Space

The patio is more common in southern Chinese traditional dwellings and is one of Huizhou dwellings' most distinctive architectural features [14]. The patio is not thought of as a conventional fully open courtyard in terms of the type of architectural area. In order for Huizhou dwellings to share the outdoor environment as the interior environment, it is between the "inside" and "outside" of the building, connecting the outdoor environment and the inner space and creating an "outside area" inside the building. The patio will, however, have some effect on the natural illumination in the actual situation. This paper highlights the patio of the traditional Huizhou architectural space with field research as the major focus, combined with the study of Huizhou dwellings, in order to investigate the impact of the space adjacent to the patio.

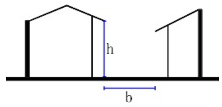
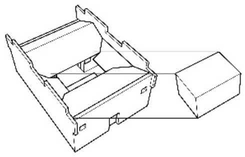
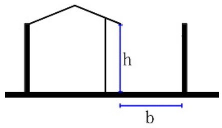
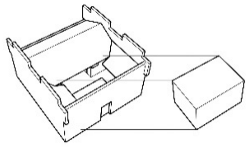
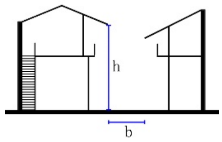
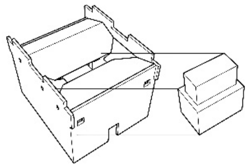
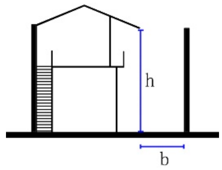
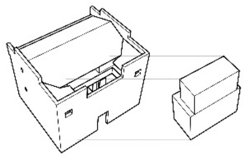
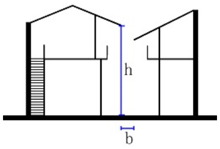
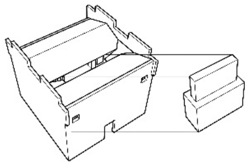
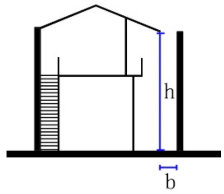
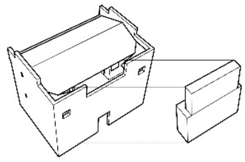
Since san-ho-yuan and si-he-yuan are the two primary spatial types of Huizhou dwellings, the patio may also be split into these two groups. The main room, the two sides of the veranda, and the courtyard wall serve as the interface of the patio in the san-ho-yuan. The main room, the two sides of the veranda, and the reversely-set house form the si-he-yuan's patio's interface. In a two-story building, for example, the spatial components of the patio from top to bottom are the roof, the top floor enclosed space, the floor slab, the bottom floor enclosed space, and the ground. Exterior brick walls, wood panel walls, and wood framing leading up to the patio make up the multi-level spatial sequence from the outside to the inside. The site and size of the patio in such a spatial sequence are controlled by several variables and exhibit regular fluctuations in the building plan, as shown in Table 3.

Table 3. Patio spaces with different length–width ratio.

	Si-He-Yuan		**San-Ho-Yuan**	
	Plane	**Axonometric**	**Plane**	**Axonometric**
Horizontal				
				
				
				

Since the main house building is generally "three rooms and five frames", assuming the standard space composition of the san-ho-yuan and si-he-yuan courtyard as the prototype, the width of the patio is fixed, thus the interface height h (distance from the eaves to the ground) and the depth b (horizontal distance between the front and rear eaves) of the enclosed patio can be divided by h/b to obtain three types of shapes: square, rectangle and flat. The square patio (h/b $\approx$ 1), which is less common in residential buildings and more common in public buildings, is mostly found in one-story buildings. The rectangular patio is the most common in residential buildings, with a h/b of about 3/1 to 4/1 where the depth of the si-he-yuan patio b is larger than that of the san-ho-yuan. The number of flat patios (h/b $\approx$ 6/1) is less. The square, rectangular, and patio shapes are shown in Table 4.

Table 4. Patio spaces with different depth–width ratio.

h/b	Si-He-Yuan		San-Ho-Yuan	
	Profile	Axonometric	Profile	Axonometric
Square				
Rectangular				
Flat				

5. Simulation Study

5.1. Simulation Input and Model Calibration

5.1.1. Orthogonal Experimental Design

The basic space types of san-ho-yuan and si-he-yuan are chosen for this study in light of the various patio types in Huizhou dwellings described in the previous paper and the collection of related data. The variables of design parameters such as window edge height, window width, patio length, and patio width are selected to explore the differences in their sensitivity to the daylighting performance of rooms in different space types. The different level values of the design parameters are shown in Table 5.

A technique for researching and examining the outcomes of tests with multiple influences is known as the orthogonal test design method. The orthogonal test method uses a parametric table to rationally choose the influencing factor parameters and design the test to minimize the number of tests without compromising the experimental result. The orthogonal experiment approach was frequently employed in earlier academic investigations on daylighting [21–24]. Therefore, an orthogonal experiment was used to pick a sensitivity analysis of the design parameters for this study to quickly expose the variations in the effects of the coupling results of all variables on the performance of the room daylighting.

Table 5. Design parameters of different influencing factors for the daylighting performance.

	Window Edge Height (m)	Window Width (m)	Patio Length (m)	Patio Width (m)
	A	**B**	**C**	**D**
Level 1	0.9	0.6	5.3	1.0
Level 2	1.0	0.9	7.8	2.0
Level 3	1.1	1.2	10.2	4.0
Level 4	1.2	1.5	-	-

The orthogonal experiment table with four design parameters was generated based on the IBM SPSS Statistics 26, and the orthogonal experiment table was used to generate a total of 16 sets of experiments using L16 (44). Since only three values were set for the patio width and patio length, the orthogonal experiment table was modified according to the combined fitted level method, and a total of 16 sets of orthogonal models were obtained (Figure 7) for the simulation.

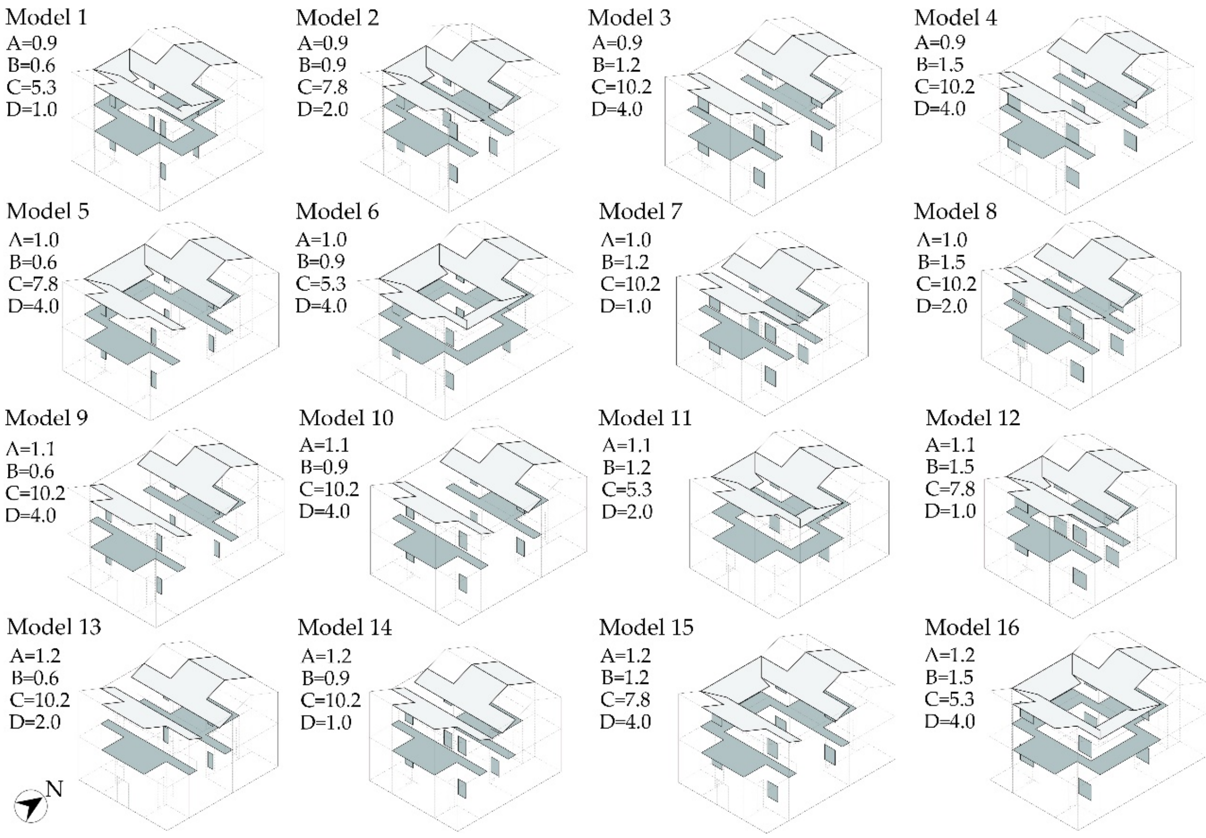


Figure 7. Si-he-yuan patio orthogonal model.

5.1.2. Model and Parameter Setting

This study uses the plug-ins Ladybug1.5 and Honeybee1.5 in Grasshopper, which are computational daylight simulation plug-ins based on the rhino modeling software developed with the Radiance and Daysim engines, and the simulation flow is shown in Figure 8.

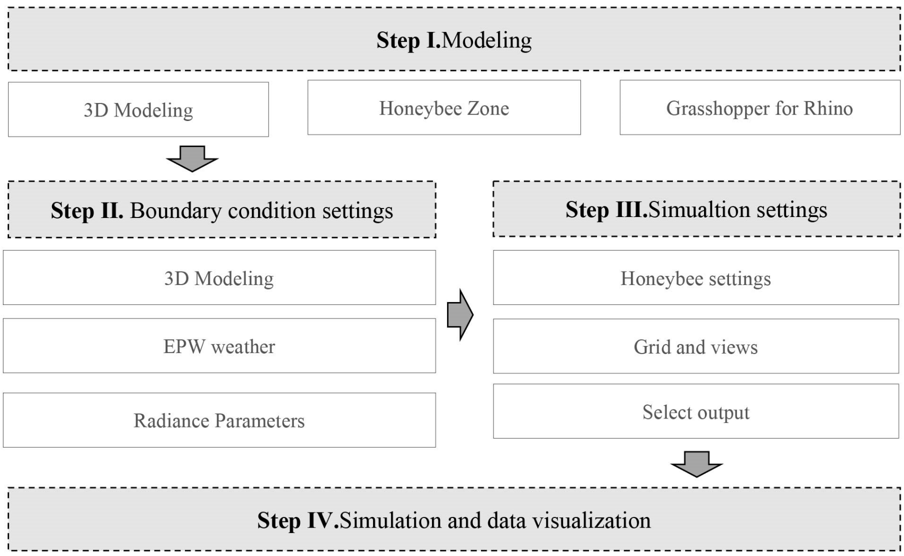


Figure 8. Daylighting simulation process.

Honeybee can simulate and calculate most of the performance evaluation indicators, including natural daylighting performance evaluation indicators such as DF, Daylight Autonomy (DA), sDA, etc., and glare evaluation indicators including DGP, DGI, etc. DA can represent the proportion of the space's measuring points' annual daytime hours that are over the designated daylighting level. According to the Chinese building lighting design standard (GB50033-2013) [25], the standard value of indoor natural illuminance in residential buildings is 300 lx, thus 300 lx was selected as the illuminance threshold for simulation to judge the daylighting performance of the room. sDA is the portion of the measurement grid that is greater than the set illumination threshold, which is typically set at 50%. UDI is the percentage of natural light in the effective illumination range time on the working plane over the course of a year. This indicator pertains to the assessment of the effectiveness of natural daylight, which is neither too dim nor too bright. In this study, 100 lx was chosen as the lower threshold and 2000 lx as the upper threshold. Window glare is measured using the DGP, which represents the percentage of people that are disturbed by glare. DGI is used to assess how uncomfortable window glare is.

In this study, the evaluation indices for natural daylighting were DA, sDA, UDI, DGP, and DGI. Daylight simulation results were influenced by climate and material parameters as well as the quality module in honeybee, which affected the simulation accuracy. Two was chosen for this simulation to represent the highest simulation accuracy. According to the Chinese building lighting design standard (GB50033-2013) [25], the test surface of this paper was chosen to be 0.75 m from the room floor, and the EPW file from the weather station of Tunxi, Anhui Province, in the typical weather year of CSWD China, was used for the climate file to ensure that it is as close to the real situation of the building as possible. The glare simulation was chosen to be conducted at 14:00 on 22 December, when the sun's altitude angle is high and prone to glare. The remaining settings of the simulation are shown in Table 6.

Table 6. Simulation parameter setting.

Reflectance (%)	Wall 0.8		Floor 0.1		Roof 0.7	
Radiance parameter	-ab	6	-c	1	-dt	0.15
	-ad	25,000	-dc	0.75	-lr	8
	-as	4096	-dp	512	-ss	1.0
	-ds	0.05	-dr	3	-st	0.15

5.1.3. Simulation and Experimental Validation

During a summer day with sunny weather, this study measured the daylighting levels in the major rooms every half-hour. We attempted to select a time when the test was less impacted by clouds to limit the inaccuracy because the sun was occasionally hidden by clouds in the sky, which had a significant impact on the data during the test. The daylight in the bedroom was determined to be between 0.1 and 30.2 lx throughout the day and less than 10 lx the majority of the time during the actual measurement, which is not particularly useful for simulation. In order to simulate the two patios at the front and back of the residential house as well as the hall in the backyard under clear sky conditions, the building model constructed by the measured dimensions was simplified and imported into Honeybee 1.5 The results are shown in Figure 9.

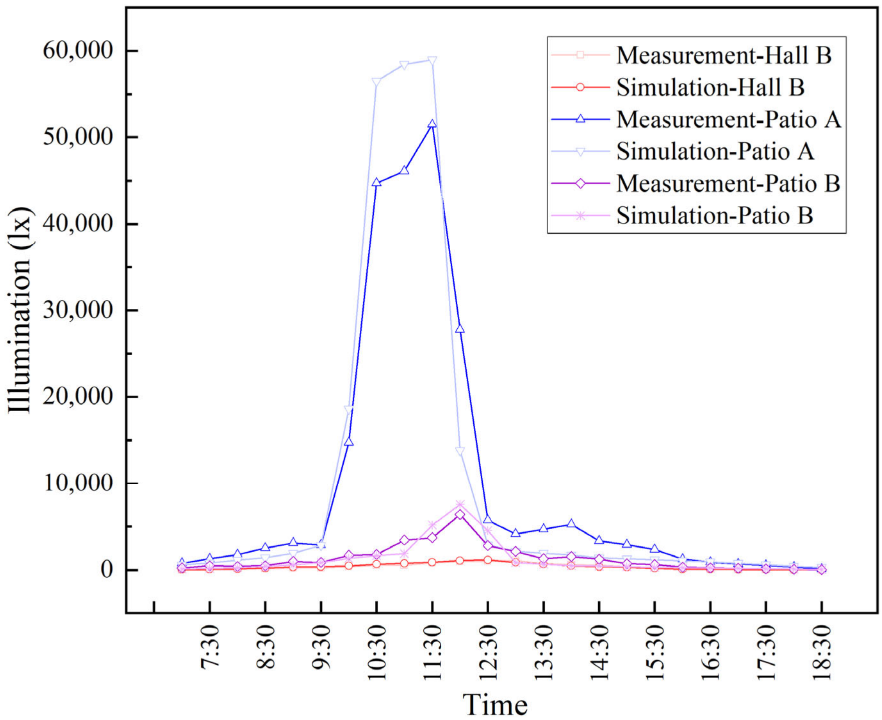


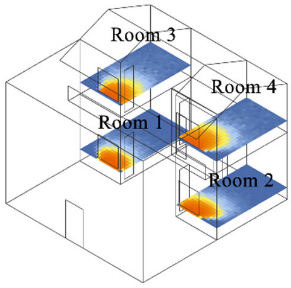
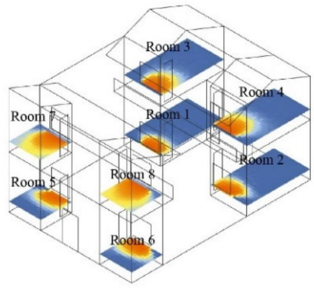
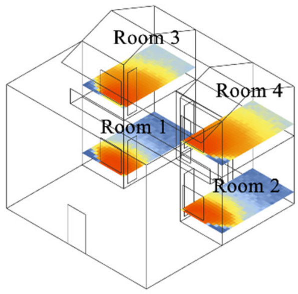
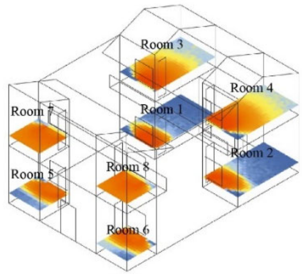
Figure 9. Simulation and measurement results.

The figure shows that there is a significant difference between the two patios' highest values of illumination between 10:00 and 12:00. This is because Patio B is surrounded by two-story buildings with subpar daylighting, but Patio A's front is a one-story building with excellent daylighting. In addition to the building in the real measurement, Patio A also contains green plants and other detritus, and the ground splashing water is more humid, which lowers the reflection coefficient. As a result, the simulated maximum value of Patio A is higher than the measured value. Patio B is further north than Patio A. The maximum value occurs at around 12:00, which is smaller overall than the simulated value but can be used as a validation since the difference is not significant. The illuminance of Hall B is relatively low compared to the two patios. However, the interior furniture is numerous and the reflection is more complicated. The measured curve is not as smooth as the simulated curve, but the trend is similar, thus it can be used as a verification.

5.2. Analysis of Multi-Factor Coupling

The daylighting performance-related parameters sDA, UDI, and DGP are obtained by simulating the orthogonal models of the san-ho-yuan and si-he-yuan using the design parameters. The orthogonal model four is chosen for comparison and analysis after the simulated data have been compiled and examined. This analysis reveals that while there is a slight variation in the values of the daylighting performance-related parameters, the distribution of natural daylight in the south-facing rooms of the san-ho-yuan and si-he-yuan is roughly the same, as shown in Table 7. This study chooses the si-he-yuan for analysis and discussion to more effectively illustrate the impact of the main rooms and avoid needless repeating of the topic. In addition, we chose Room 4 on the west side of the south-facing second floor as the primary research object to facilitate the demonstration and further investigation of the weights of each influencing factor to explore more significantly the influence of each influencing factor on the room daylighting performance.

Table 7. Comparison of daylighting performance parameters of model 4 of san-ho-yuan and si-he-yuan.

Daylighting Performance-Related Parameters	San-Ho-Yuan	Si-He-Yuan
sDA(%)	 Room 1 = 13.9 Room 2 = 15.6 Room 3 = 18.7 Room 4 = 21.8	 Room 1 = 12.3 Room 2 = 14.1 Room 3 = 16.7 Room 4 = 18.5 Room 5 = 32.7 Room 6 = 36.5 Room 7 = 50.6 Room 8 = 68.0
UDI(%)	 Room 1 = 26.9 Room 2 = 26.5 Room 3 = 57.5 Room 4 = 60.7	 Room 1 = 25.9 Room 2 = 26.7 Room 3 = 56.5 Room 4 = 59.1 Room 5 = 52.7 Room 6 = 56.5 Room 7 = 74.6 Room 8 = 75.6
DGP(%)	Room 1 = 18.5 Room 2 = 21.6 Room 3 = 25.7 Room 4 = 22.6	Room 1 = 19.5 Room 2 = 22.8 Room 3 = 26.2 Room 4 = 23.3 Room 5 = 21.9 Room 6 = 23.2 Room 7 = 25.0 Room 8 = 31.6

The sDA, UDI, and DGP obtained from the daylighting simulation of Room 4 in the orthogonal model of 16 quadrangular Huizhou dwellings were compiled and plotted in Figure 10. In Model 4, in Figure 10, Room 4's sDA and UDI both attained their maximum values of 18.5% and 59.1%, respectively, showing that the room had a higher percentage of naturally illuminated spaces and greater natural daylighting overall. While Room 4 in Model 1 had the lowest natural daylighting with a sDA of 0.5% and a minimum mean of 2.2%, it was clear that all four parameters had an impact on the room's daylighting performance. In contrast, Model 16's DGP (26.5%) is the highest among the 16 models, which is lower than the value of 35% (Upper limit of imperceptible glare threshold). It means that the glare of all Huizhou dwellings is imperceptible glare.

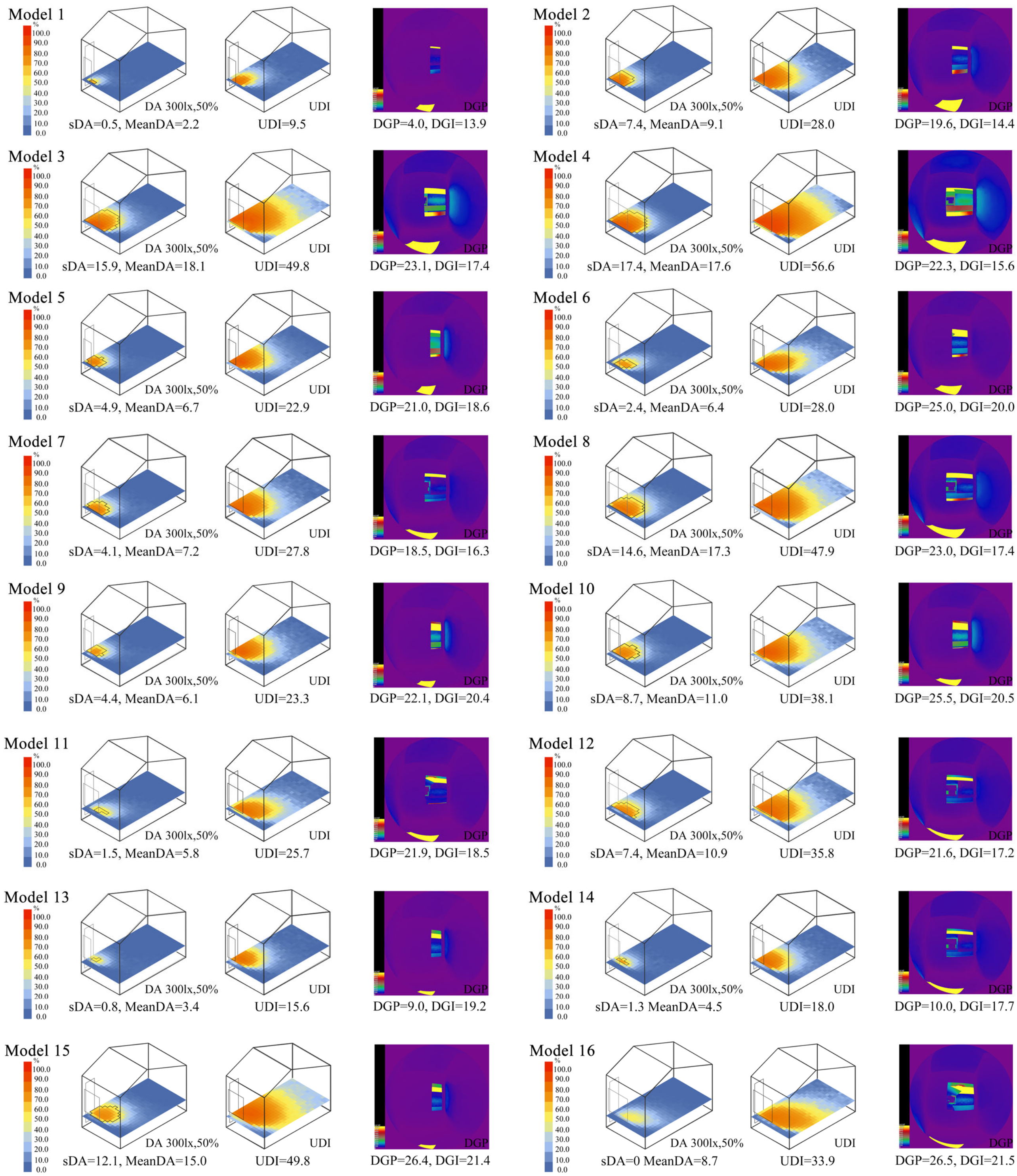


Figure 10. Simulation results of 16 orthogonal models.

In conclusion, low illumination levels and unpleasant daylighting conditions may result from the extreme settings of the design parameters; therefore, a single-factor influence analysis was created for this study to further examine the influence of each design parameter.

5.3. Single-Factor Analysis

This study performs a single-factor analysis for window edge height, window width, and patio length and width to more thoroughly analyze the effects of various design parameters on the daylighting performance of traditional Huizhou dwellings and to establish a realistic design range. Reference values for each design parameter were established based on field research of Huizhou dwellings and related data, and these values are displayed in Table 8. Since the DGPs are all within 35% of the imperceptible glare range, we will not expand to study their changing laws. Instead, we will use DA and UDI as the primary daylighting performance indices based on the simulated findings of the orthogonal test.

Table 8. Design parameters' values in single-factor impact analysis.

Experimental Group	Group	Window Edge Height (m)	Window Width (m)	Patio Length (m)	Patio Width (m)
Reference group	T0	1.1	1.5	7.75	1.0
	T1-1	0.9			
Test 1	T1-2	1.0	1.5	7.75	1.0
	T1-3	1.1			
	T1-4	1.2			
	T2-1		0.6		
Test 2	T2-2	1.1	0.9	7.75	1.0
	T2-3		1.2		
	T2-4		1.5		
	T3-1			5.3	
Test 3	T3-2	1.1	1.5	7.8	1.0
	T3-3			10.2	
	T4-1				1.0
Test 4	T4-2	1.1	1.5	7.75	2.0
	T4-3				4.0

5.3.1. Window Edge Height

In this study, four groups of models T1-1 to T1-4 were created to investigate the effect of window edge height on the daylighting performance of rooms in Huizhou dwellings. The relevant parameters were obtained by simulating and analyzing the room daylighting performance of these models, as shown in Figure 11. The changes in DA and UDI inside the room as the room depth changes are depicted in Figure 11a,b. Rooms 4 and 6 were chosen for investigation in this study to assess the impact of room location on daylighting performance.

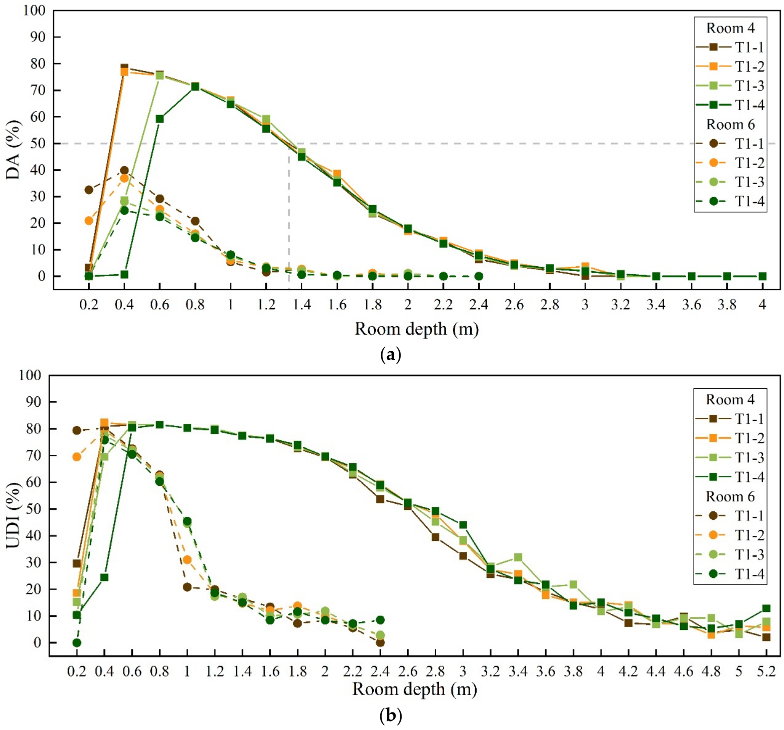


Figure 11. The effect of window edge height changes on room daylighting performance. (**a**) DA, (**b**) UDI.

As the height along the window gradually increases, as shown in Figure 11, the DA and UDI values of Rooms 4 and 6 near the window location gradually reduce, and the extreme values of DA and UDI in the room also gradually decrease. The change in window edge height has a higher impact on the DA values for Room 6 than for Room 4 as the room depth increases. Only the closed windows in Rooms 4 DA and UDI and Room 6 UDI are affected by window edge height, and once the depth of the space reaches 0.6 m, there are very few changes to the room's daylighting characteristics. The proper depth of daylight intake is determined to be the depth at which the DA value hits 50%. For window heights varying from 0.9 to 1.2 m, Room 4 reaches a suitable daylight range at around 1.34 m. The DA values of Room 6 are all below 50%, and there is no suitable daylight depth.

In conclusion, changing the height of the window edge does not significantly affect the room's internal daylight performance, but it is possible to suitably lower the height of the window edge to enhance the daylighting effect close to the window.

5.3.2. Window Width

In this study, four models from T2-1 to T2-4 were created to evaluate the impact of window width on the effectiveness of room daylighting. The parameter settings of the four models revealed a rising tendency. The results of the daylight analysis obtained from the simulation are shown in Figure 12a,b.

The DA values for Rooms 4 and 6, likewise, rise as the window width steadily widens, as shown in Figure 12. For Room 4, the rate of DA increases gradually slows down as the window width grows; the amount of DA change is less when the window width changes from 1.2 m to 1.5 m than when it does from 0.6 m to 0.9 m. The same tendency appears in Room 6, but when the window width is increased to 1.2 m, the difference in DA becomes insignificant. There is no optimal room depth value as the window width changes. Room 4 reaches DA 50% of the appropriate at widths of 0.76 m, 1.0 m, 1.2 m, and 1.35 m in that order, yet Room 6's DA values remain all below 50%.

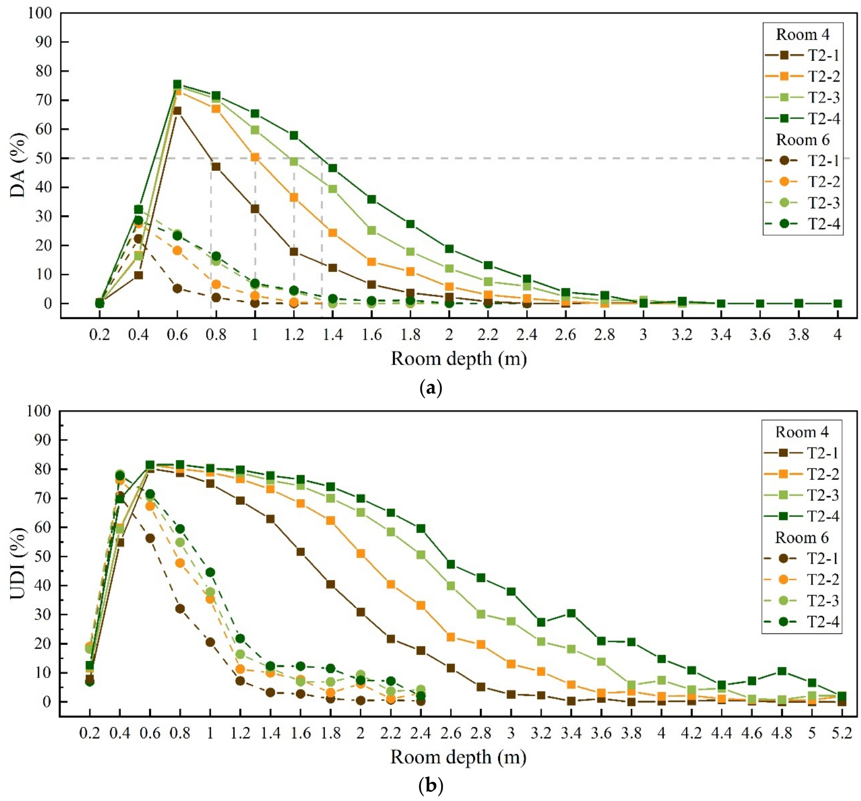


Figure 12. The effect of window width changes on room daylighting performance. (**a**) DA, (**b**) UDI.

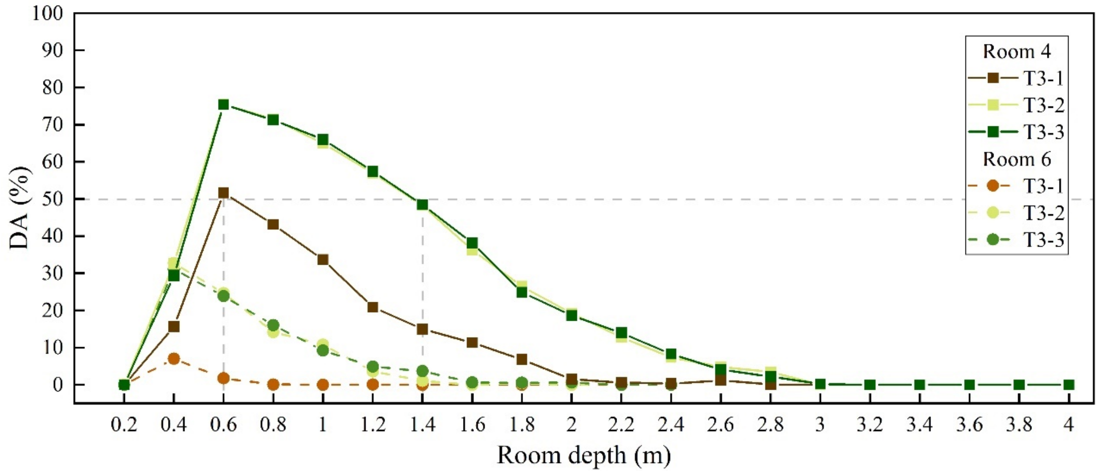
The variation pattern in Figure 12 shows that the DA of Rooms 4 and 6 with a change in window width is roughly the same as the change in UDI, with the change in Room 6 showing a minor difference. The increase in the UDI value exhibits a notable decreasing tendency when the window width parameter is set to 0.9 m.

In conclusion, the daylighting effect of the room has improved over time as the width of the window has increased. As a result, if you want better natural daylighting, widen the window as much as you can.

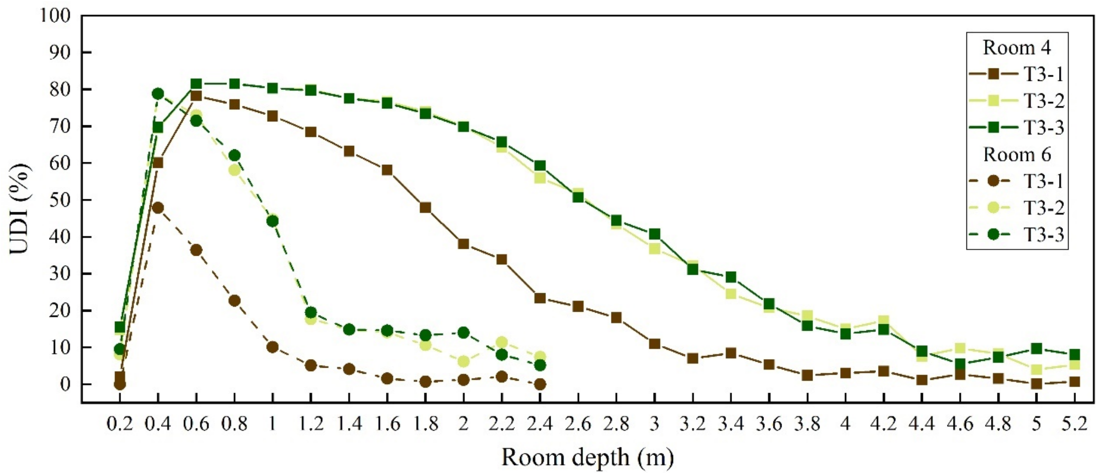
5.3.3. Patio Length

In this study, three models from T3-1 to T3-3 were created to evaluate the patio length's impact on room daylighting's effectiveness. The setting of parameters was determined according to the literature investigation and actual measurement of the length of the patio in the patio space in Section IV. The results of the daylight analysis obtained from the simulation are shown in Figure 13a,b.

As shown in Figure 13, with the increase of the length of the patio, the DA of Room 4 and Room 6 increased in general, and reached the peak when the length of the patio was 7.8 m. The simulation results of T3-2 and T3-3 are overlapped. With the increase of room depth, the increase of DA in Room 4 and Room 6 gradually weakened. When the length of the daylighting patio is 5.3 m and 7.8 m, and the depth of Room 4 is 0.6 m and 1.4 m respectively, DA reaches 50%. However, regardless of the depth of Room 6, DA value is always lower than 50%.



(**a**)



(**b**)

Figure 13. The effect of patio length changes on room daylighting performance. (**a**) DA, (**b**) UDI.

In Figure 13b, when the patio length reaches 7.8 m, the UDI ceases to change in both Room 4 and Room 6. The fluctuation trend is the same in Room 6 UDI and DA. However, as the patio length increases and the room UDI increases with the room depth, Room 4 exhibits an increase and then a decrease in the difference between the two places.

In conclusion, the daylighting performance of the room has attained a good daylighting effect when the patio length reaches 7.8 m. Even if the length of the patio is increased, it will not have an impact on the daylighting effect of the room.

5.3.4. Patio Width

In this study, four models from T4-1 to T4-3 were created to evaluate the impact of patio width on the effectiveness of room daylighting. The parameter settings of the four models revealed a rising tendency. The results of the daylight analysis obtained from the simulation are shown in Figure 14a,b.

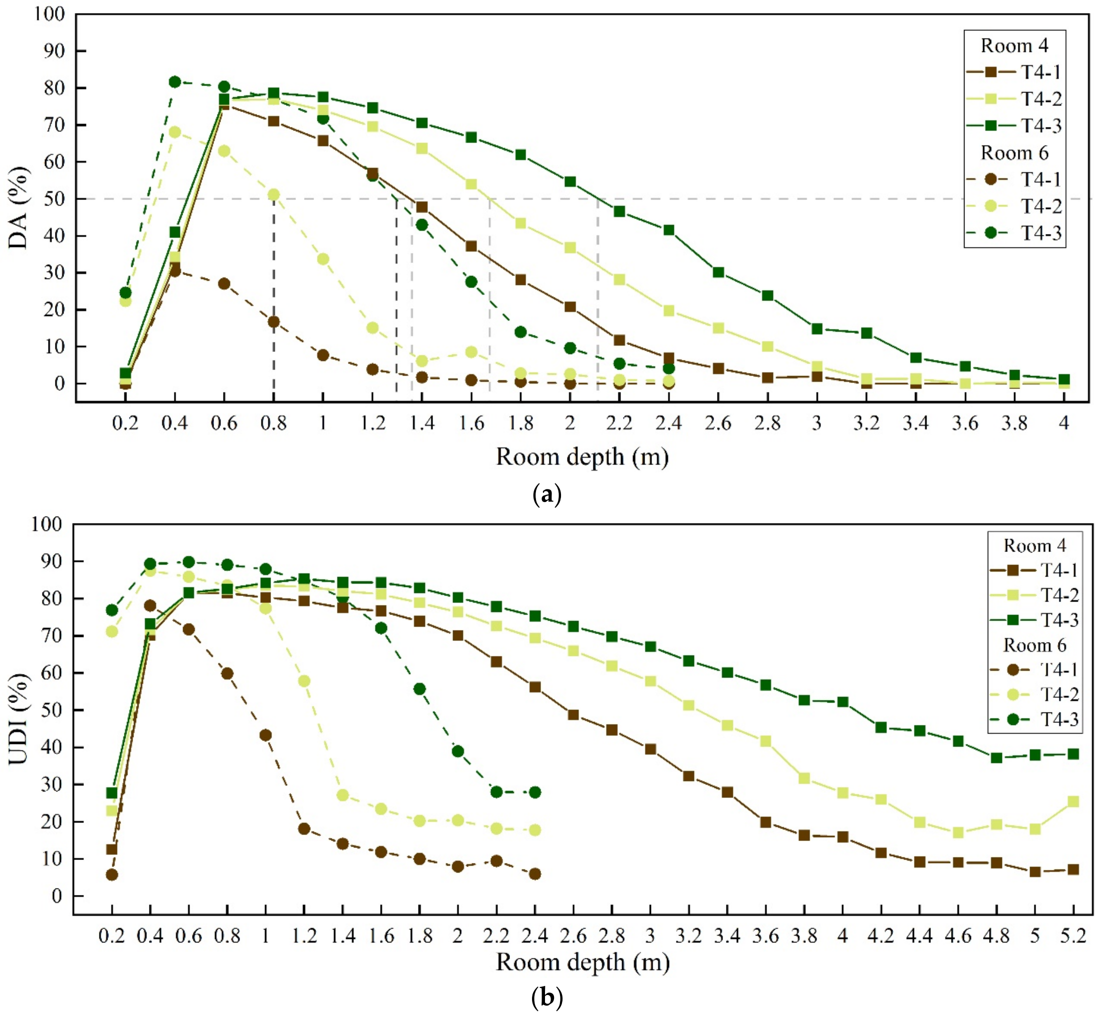


Figure 14. The effect of patio width changes on room daylighting performance. (**a**) DA, (**b**) UDI.

It can be seen from Figure 14 that the DA of Room 4 and Room 6 have increased with the increase in the length of the patio. When the width of the patio is 1 m, the maximum value is reached at the room depth of 0.6 m, and, then, DA gradually decreases with the increase in the room depth. When the width of the patio is increased to 2 m, the maximum DA of Room 4 is delayed to 0.8 m of the room depth, and, then, DA gradually decreases with the increase in the room depth. When the patio width increases from 1 to 2 m in Room 4, the rate of change in DA is a little slower than when it increases from 2 to 4 m. For Room 6, however, the DA fluctuates greatly, and the rate of change is slightly faster when the patio width increases from 1 to 2 m than when it increases from 2 to 4 m. The daylighting of space is more affected by variations in patio width than by other design parameters. In Room 4, with the three patio width design parameters, the suitable room depth is approximately 1.36 m, 1.68 m, and 2.12 m, respectively. Room 6 appears to have a DA of more than 50% daylight, and when the width of the patio approaches 2 and 4 m, respectively, the proper room depth for a DA of 50% is roughly 0.8 and 1.3 m.

Although the variation trends of Room 4 and Room 6 UDI in Figure 14 are similar to those of Room 4 DA, the UDI is still in the rate of change growth phase when the room depth reaches its maximum due to the maximum room depth of 5.2 m. Room 6 appears to be larger than Room 4 at the extremes of Room 4 and Room 6 UDI, indicating that Room 6 is more affected by the width of the patio.

In conclusion, the daylight performance of the room improves progressively with patio width and has a greater influence on the daylight performance of the room than any other design parameters.

6. Conclusions

The patio space blurs the boundary between indoor and outdoor spaces, and, at the same time, plays a buffer space role for the physical environment of the building. As a fuzzy space between the building and outdoor space, it integrates light, wind, heat, and other factors into it and improves the indoor microclimate by exchanging with the natural environment. Taking patio space as the breakthrough point, this paper studies the impact of different patio space types on lighting of adjacent residential space. Specific conclusions are as follows:

1. Aiming at the patio space of Huizhou traditional dwellings, this paper summarizes and generalizes the common space forms of san-ho-yuan and si-he-yuan. Taking the san-ho-yuan and si-he-yuan as the prototype, it summarizes three different patio space forms under different aspect ratios: square, rectangle, and flat.
2. Based on the measured data of poor natural lighting in the adjacent building space of the patio, the optimization possibility of key design parameters of the patio was explored, including window edge height, window width, patio length, and patio width. The multi-factor orthogonal model of the san-ho-yuan and si-he-yuan courtyard was simulated according to the design parameters. The areal distribution range of natural lighting in the south-facing rooms of the si-he-yuan and san-ho-yuan san-ho-yuan was roughly the same. Moreover, the extreme setting of design parameters may lead to unsatisfactory lighting conditions.
3. The height of the window edge had the greatest influence on the natural lighting near the window. Therefore, to optimize the natural lighting effect near the window, the height of window edge can be reduced appropriately. Increasing the width of the window and the width of the patio can improve the overall lighting of the room, and the optimal value of the patio length is 7.8 m.

This paper studies the influence of different key design parameters of patio space on daylighting, and guides the early daylighting design and transformation of Huizhou traditional dwellings and new buildings. While maintaining the spatial characteristics of Huizhou traditional dwellings, it provides a more reasonable and scientific daylighting mechanism for the internal residential space.

Author Contributions: R.G.: methodology, formal analysis, writing-original draft; J.L.: resources, supervision; Z.S.: writing—original draft preparation, software; G.Z.: writing—reviewing and editing, visualization; W.Y.: conceptualization, supervision, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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