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Research on the Range of Appropriate Spatial Scale of Underground Commercial Street Based on Psychological Perception Evaluation

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Research on the Range of Appropriate Spatial Scale of Underground Commercial Street Based on Psychological Perception Evaluation

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Featured Application: (1) Interdisciplinary interaction between environmental psychology and architectural design theory. (2) Application of Virtual Reality technology for human cognitive evaluation. (3)Mastery of the suitable length range and related laws of human cognitive change in underground commercial street spaces. (4) Confirmation of significant cognitive impact under different scale combinations on human perception.

Abstract: Developing and utilising of underground space is an vital direction for urban growth. Underground commercial streets, as a significant component of underground space accommodating extensive human social activities, and consequently necessitate the creation of human-scale spaces. In the evolution of urban design development towards greater refinement, applying architectural theories and excessively subjective designs has resulted in a deficiency of human-centered design and a disordered spatial environment. This study merges environmental psychology and architectural theory to determine the appropriate length of spatial scale. Two experiments focusing on spatial perception evaluation were conducted using a virtual experimental platform that featured varying dimensions of spatial scale combinations. These quantified combinations were correlated with perception evaluation, and regression analysis was employed to identify appropriate scale ranges, which were superimposed on the range of length selection. Finally, the optimal length and scale combination for underground commercial street spaces were established, providing a reference for the human-centered design of these environments.

Keywords: virtual reality; underground commercial street; Appropriate Spatial Scale; Multidimensional Scale; perception evaluation

1. Introduction

The rapid increase in urban population has presented a new challenge to the spatial capacity of large cities. Consequently, the expansion of underground space has emerged as a critical option for future urban development[13], Recent developments in underground spaces, however, continue to face issues such as poor systematic planning and outdated methodologies [3]. In the development of urban underground commercial streets, it is essential to focus on creating more human-centered spatial scales. However, the current design of street space at the urban scale, influenced by modern architectural theories and the predominance of subjective creativity, have led to a disconnection between theory and practice, resulting in a lack of human-centered design and disorder in the spatial environment. This study takes the appropriateness of spatial scale as one of the important means of judging spatial quality.

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Early spatial research explored the human scale as a crucial metric for assessing street spaces[9]. Scholars conducted spatial perception experiments focusing on emotional experiences[12], psychological problems[2], and comfort[16]. They introduced environmental psychology theory, integrating human subjective feelings with design, establishing the groundwork for human-centric spatial quality research. However, spatial quality evaluation suffers from redundancy, limited research approaches, and a lack of integration with real-world settings for experimentation. Consequently, it predominantly investigates issues from isolated dimensions, lacking systematic and scientific rigor.

Spatial appropriateness, regarded as a crucial criterion in assessing the human scale[21], is progressively garnering research attention. MATZARAKIS A examine individuals' comfort levels by analyzing their physiological parameters alongside environmental factors[17]. Fang Zhiguo investigates the appropriateness of street space scale, offering design strategies through SPSS and SD analysis[15]. D Hudec (2023) develop a methodology for calculating space capacity parameters and assessing shared space appropriateness, focusing on transportation aspects[18] .In research practice, there exists a deficiency in perception evaluations of spatial appropriateness and a scarcity of direct empirical evidence regarding the specific impact of appropriateness on street spatial quality. Increasingly, scholars have integrated field research and street maps into their studies, exemplified by Liu Qing studied the walking perceptual experience of urban street space and suggested optimization strategies[10]. Jingxian Tang and Ying Long employed image segmentation techniques to segment the streetscape and extract street elements for evaluating the five dimensions of spatial quality proposed by Ewing and Clement[5]. Zhang F (2018) conducted empirical studies in Beijing and Shanghai to explore the correlation between perceived quality and visual elements [19]. Zhang L（2019) [20]and Vukmirovic, Milena (2022) [14], among others, utilized web-based data such as location-based data (LBS), Twitter data, and Points of Interest (POIs) to extract factors potentially related to the quality of public spaces and investigated the relevance of this data for urban design and pedestrian space enhancement. Conducting research on street space quality solely through field research overlooks potential interfering factors in real environments, leading to highly variable research outcomes. Similarly, utilising street maps and big data fails to integrate with actual scenes for in-depth analysis. Hence, this study employs a virtual reality experimental platform to construct street scene models, enabling subjects to evaluate spatial quality in a virtual reality setting. This approach aims to minimize the impact of irrelevant factors while obtaining precise data.

Environmental differences between aboveground and underground spaces may impact human perception differently. With the increasing influence of underground space development on urban development, most scholars have been researching humanised spatial quality. Elena Romanova (2016) explored underground buildings. It analysed the problems related to the negative psychology of users[11], and Jisun Kim (2016) [4]explored the psychological impact of underground transport spaces on passengers [12] and carried out a survey on the anxiety of passengers; in both of the above studies, the psychological feelings of the users were considered mainly in terms of the functional dimension, with the additional impacts caused by other influencing factors were neglected. Li Z (2017) analysed the external design of underground shopping streets with case studies[6]. They put forward relevant design suggestions, but the study was detached from people's subjective perception evaluation and lacked objective experiments' support. Ding, Shanmin investigated the psychological cognition of side interfaces in underground streets through the efficient simulation properties of VR, suggesting that the material characteristics of the side interfaces had an impact on participant preferences [7]. However, they did not consider the relationship between the spatial scale combinations and the influence of psychological cognitions. Xu Yao took the underground commercial street guidance sign as the research object, analysed the data through eye tracking and other techniques, and put forward the design suggestions to improve the visual saliency of the guidance sign[8]. In this experiment, the two-dimensional street image was used to simulate the actual three-dimensional visual guidance situation. The experiment ignored the perception difference between stereo and planar in the simulation problem. Despite their significant correlation with human psychology, scant research addresses the optimal length of underground commercial

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streets[27]. A appropriate length can enhance individuals' time engaging in activities within street spaces. Moreover, alterations in the spatial scale of underground commercial streets can influence people's perception evaluations of the environment.

In the research on scale combinations,Yoshinobu Ashihara[1] studied scale combinations such as D/H in two-dimensional scale combinations, forming a particular theoretical foundation. However, more needs to be done to research spatial scale combinations in other dimensions. In the underground commercial street space scene, in addition to the two-dimensional scale combinations, the three-dimensional scale combinations can reflect the depth perception, and the validation of the two-dimensional scale requires the value of the one-dimensional scale, and the three scale combinations are closely connected, in which the length element is consistent with the direction of the pedestrians' behavioural paths so that the appropriate lengths under different spatial scale combinations are worth in-depth research.

This study will be guided by environmental psychology and architectural theory, taking the urban underground commercial street as the primary research object, cutting in from the perspective of scale combination, obtaining the perception evaluation data under different modelling scenarios, and researching the relationship between the influence of one-dimensional, two-dimensional, and three-dimensional scale combinations on the spatial appropriate lengths, to explore the appropriate length range and scale combinations of the underground commercial street.

2. Materials and Methods

2.1. Research Scope

The research objective of this paper focuses on the scale combinations of underground commercial streets. In order to create a more realistic experimental model, the author collected essential scale data of underground commercial streets in urban areas. The research locations mainly include underground streets in commercial complexes, and the research objects are the underground commercial streets that connect nodes in these underground streets. Shanghai, situated in East China, stands as a global metropolis interweaving international economy, finance, and trade, boasting a plethora of expansive underground commercial avenues. Nanjing, the capital city of Jiangsu Province, serves as a pivotal transportation nexus within the Yangtze River Delta, experiencing rapid commercial growth in recent years and offering significant reference value. Xuzhou, situated in the northwestern region of Jiangsu Province, anchors the Huaihai Economic Zone, boasting substantial potential for commercial advancement. Chengdu, a significant economic and cultural epicentre in Southwest China, doubles as a trade, logistics hub, and comprehensive transportation nexus, showcasing a robust underground commercial street infrastructure that offers valuable inspiration for the study. Therefore, 62 underground commercial streets in the above cities were selected for scale measurements, which included the length, width and height of the underground commercial streets(Figure 1).

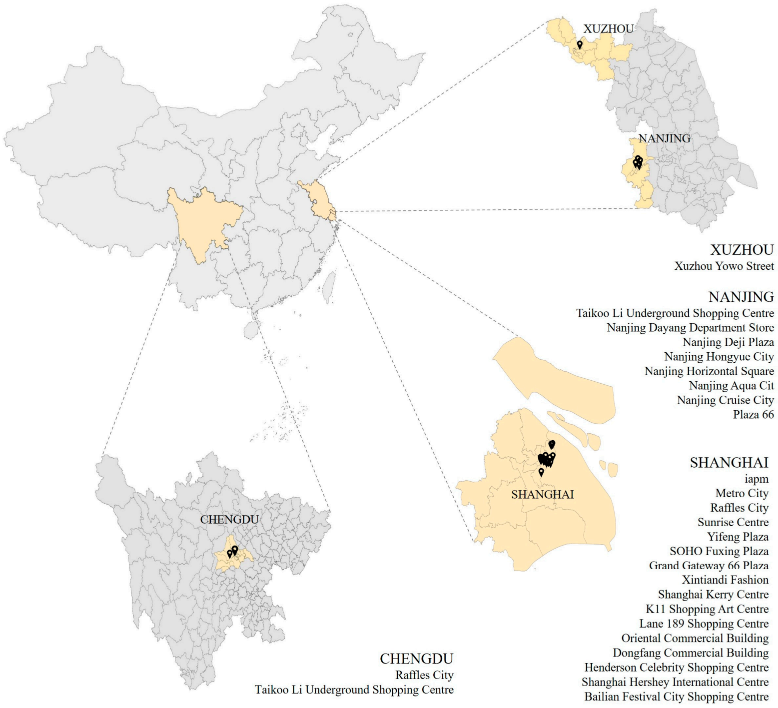
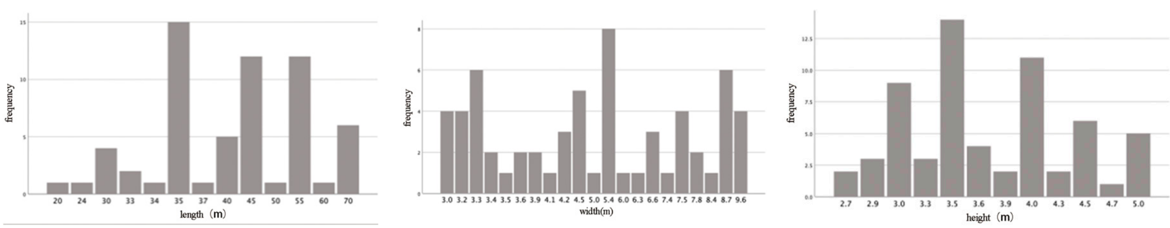


Figure 1. Location of the research object.

2.2. Data Processing

In this paper, an experimental model was constructed by analyzing the basic data information of 62 underground commercial streets in five cities for frequency analysis. The high-frequency scale values, which representing the scale values of the underground commercial streets in our research, were identified based on the frequency histogram (Figure 2). For further analysis, higher frequency values were selected for length, width and height. Specifically, the selected values for length were 35m, 45m, 55m, and 70m; for width, they were 3.3m, 5m, and 8.7m; and for height, they were 3m, 3m, 5m, and 4m. Additionally, the values of 35m, 45m, 55m, and 70m for length; 3.3m, 5.4m, and 8.7m for width; and 3m, 3.5m, 4m, 4.5m, and 5m for height were also included. The scale model of the underground commercial street constructed using this data serves as the foundation for our experimental study, enabling us to draw more practical conclusions.



(a) High-frequency length (**b**)high-frequency width (C)high-frequency height

Figure 2. Frequency diagram of length, width and height of underground commercial street.

2.3. Experiment Content and Steps

In this paper, in order to explore the appropriate range of underground commercial street length, based on the scale research data to complete the following two virtual simulation experiments (Figure 3):

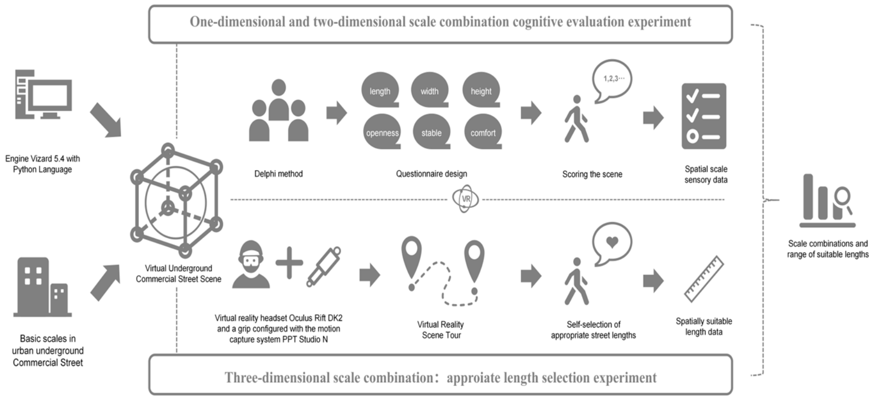


Figure 3. Research Methods and Processes.

Experiment 1: One-dimensional and two-dimensional scale combination — perception evaluation experiment

Based on the scale data collected from the research of the actual underground commercial street, virtual reality technology is used to construct underground commercial street models with different scale combinations. In the virtual simulation model, participants were instructed to assess various street scale combinations using a questionnaire comprising six adjectives rated on a 1-7point scale. This approach aimed to assess spatial perception evaluation data quantitatively. Subsequently, mathematical and statistical analyses were employed to investigate the impact of one-dimensional and two-dimensional scales on perception evaluation, considering parameters such as length, width, and height. This analysis identified the most influential elements, clarifying their correlation with perception scale data. Verification was conducted through coverage analysis. Finally, based on these findings, an appropriate length range was deduced using a combination of one-dimensional and two-dimensional scales.

Experiment 2: Three-dimensional scale combination——appropriate length selection experiment

Based on the scale data collected from the research of the actual underground commercial street, virtual reality technology is used to construct underground commercial street models with different scale combinations. Subjects with helmets and handles could travel and stay in the underground commercial street with fixed width and height values. The selection of the appropriate length in the virtual scene was recorded in real-time. A holistic three-dimensional range of appropriate scale combinations was obtained through the superposition analysis and visualisation of the data.

In this study, we will combine the appropriate length range obtained from the perception evaluation experiment of Experiment 1 and the appropriate length selection results of Experiment 2 to verify each other, find the typical characteristics of the appropriate scales, and finally obtain the appropriate length range and scale combinations affecting the spatial cognition of the underground commercial street.

2.4. Questionnaire Setting and Evaluation Index Establishment

The sub-experiment used the Delphi method[22] to determine the evaluation indicators of spatial cognition. A leading group of three research saints, 20 students and ten in-service teachers of architecture and related disciplines formed a panel of experts to select and evaluate the indicators. In the first consultation, the study categorised the indicators in the articles evaluated in the past streets: scale cognition and ambience cognition. The experts screened 30 common adjective pairs about spatial cognition, including indicators such as safe[23], lively[24], comfort[25], and beautifully[26] from the articles to evaluate them. In the second consultation, several anonymous feedbacks were given for the content of the first consultation to obtain a consistent opinion. Six of the 15 adjective pairs were finally selected as the spatial cognition evaluation indexes for this experiment, and the questionnaire was set up using the SD method, as shown in Table 1.

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Table 1. Spatial cognitive evaluation indexes.

Perception Classification	Evaluation aspects	Description of the level of evaluation		
		3 level	0	3 level
scale cognition	length cognition	too short	suitable	too longer
	width cognition	Too narrow	suitable	too wide
	height cognition	too low	suitable	too high
atmospheric cognition	openness cognition	confined	moderately openness	suitable
	stable cognition	unstable	moderate stable	suitable
	comfort cognition	indisposed	moderate comfortable	suitable

2.5. Experimental Design

2.5.1. Experimental Equipment

This study utilizes an immersive virtual reality system as the platform, comprising an optical position tracking system, a head-mounted display (HMD), an orientation tracking device, and a graphic workstation for monitoring and maintaining the virtual environment (VE) status (Figure 4). The laboratory room has dimensions of 6mx7m, and to accommodate the scale of the experimental model scene, subjects are required to use the system handle for seamless navigation throughout the overall experimental model.

Figure 4. Experimental equipment.

2.5.2. Participants

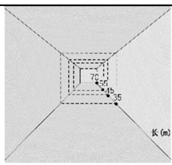
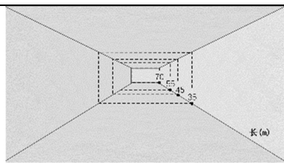
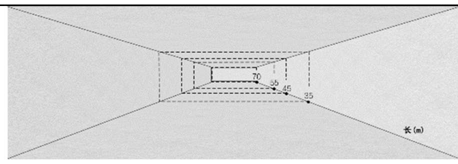
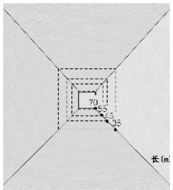
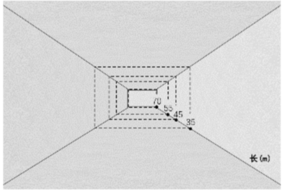
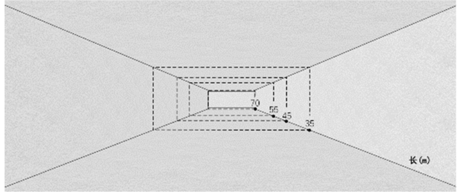
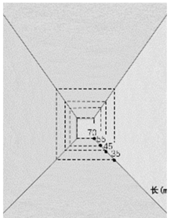
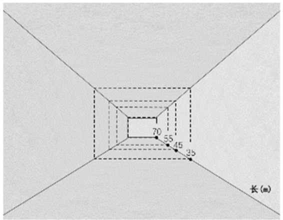
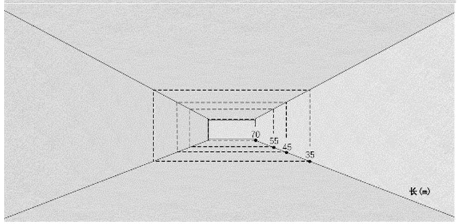
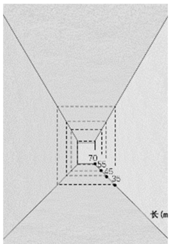
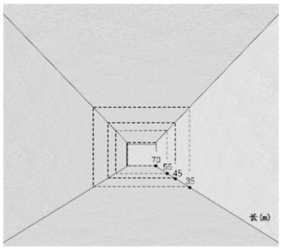
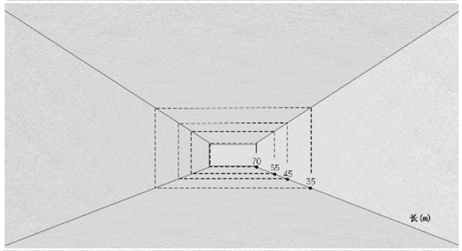
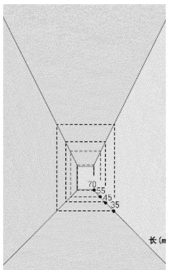
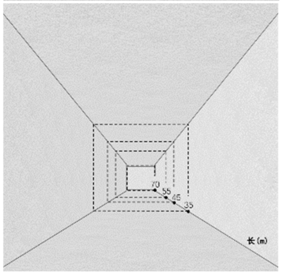
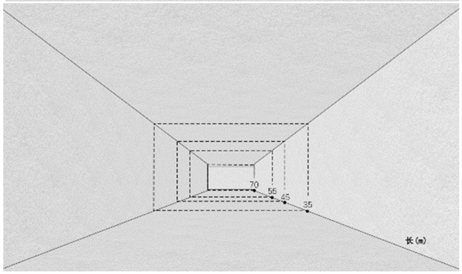
The experiment was conducted in the VR laboratory of the China University of Mining and Technology; considering that the existing main consumer population is young people and the experimental field is located in this school, weighed the coverage and practical operability of the experiment and decided to recruit school students with a significant age span, totalling 53 subjects, with an age span of 18 to 29 years old. They range from 18 to 29 years old. Thirteen samples were found to be less reliable, and 40 samples were retained as valid data.

2.5.3. Construct Experimental Model

Based on the results of the survey collection, the data on the experimental model size was constructed. The high-frequency values for length were 35 metres, 45 metres, 55 metres, and 70 metres. The high-frequency selected values for width were 3.3 metres, 5.4 metres, and 8.7 metres. Similarly, for height, the high-frequency selected values were 3 metres, 3.5 metres, 4 metres, 4.5 metres, and 5 metres. When selecting the scale elements for the experimental model, high-frequency values were chosen for the width and height scale elements.

The experimental scenes, labelled I to V, gradually increase in height, resulting in 15 underground commercial street spaces with varying length and width combination in each scene. The model spaces predominantly consist of rectilinear shapes, using white plaster as the street material and maintaining a light intensity of approximately 700lx, as shown in Table 2. Both virtual simulation experiments in this study share the same 15 scenes. The primary focus of this study is to examine the appropriate range of lengths, and thus, in experiment two, the maximum length selection range is set at 70 meters to provide more options for the subjects.

Table 2. Schematic table of experimental scenarios I-V.

	3.3m width	5.4m width	8.7m width
Scene I 3.0m height			
Scene II 3.5m height			
Scene III 4.0m height			
Scene IV 4.5m height			
Scene V 5.0m height			

Based on the analysis of previous research, this paper utilizes high-frequency data to construct various street models for underground commercial streets. These models are formed by combining five different heights (H), three different widths (D), and four different lengths (L). As a result, 60 underground commercial street models are obtained through combinations of one-dimensional and two-dimensional scales. The values of the one-dimensional and two-dimensional scale variables can be found in Table A1 of the Appendix A.

2.6. Experimental Procedure

The experiment standardized the subjects' visual height at 167cm, reflecting the average height of the participants. Within the virtual scene, offering a 360° panoramic view, measures were taken to mitigate subjects' vertigo by setting the walking speed of the handle to 1 m/s during pre-experimentation. The detailed experimental procedure is outlined as follows:

Experiment 1: One-dimensional and two-dimensional scale combination-perception evaluation experiment

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In this experiment, the subjects could navigate a virtual model of an underground commercial street using a handle. After familiarizing themselves with the environment, they were asked to return to the starting point of the street space. Subsequently, they were asked to complete a scale, where the experimenter recorded their perceptual ratings of different scale combinations of the underground commercial street. The entire experimental process lasted approximately 30 minutes.

Experiment 2: Three-dimensional scale combination-appropriate length selection experiment

After allowing the participants to navigate through a virtual scene of an underground commercial street using a handle, they were required to use the handle to select a more appropriate street length to stay on. For this experiment, the experimenter randomly presented the subjects with different scale combinations of the virtual underground commercial street scene. Initially, the subjects were allowed to explore the street entirely using the handle and choose the most appropriate length to stay on. The experimenter recorded the data length, and the complete experimental process took approximately 30 minutes.

3. Results

3.1. Analysis of One-Dimensional Scale, Two-Dimensional Scale Combination and Spatial Perception Correlation

3.1.1. One-Dimensional Scale Combination

As shown in Table 3. there is a strong correlation between one-dimensional scale combinations and perception. Each scale element is strongly correlated with its corresponding scale perception. Specifically, the correlation between the width element and the height perception is negative (P=-0.836), suggesting that as the width increases, the height of the street decreases significantly. On the other hand, the width element is highly positively correlated with the perception of openness (P=0.823), indicating that as the width increases, the perceived openness of the space also increases. Therefore, among the one-dimensional scale elements, the width element significantly impacts the perception of underground commercial streets, as it is highly correlated with width, height, and openness perception.

Table 3. Table of correlation coefficients between the combination of one-dimensional scale variables and cognitive evaluation.

		length cognition	width cognition	height cognition	openness cognition	stable cognition	comfort cognition
H	Pearson	0.156	-0.263*	0.547**	-0.293*	-0.081	-0.102
	significance	0.234	0.042	0	0.023	0.537	0.439
D	Pearson	-0.430**	0.928**	-0.836**	0.823**	0.726**	0.557**
	significance	0.001	0	0	0	0	0
L	Pearson	0.825**	0.189	0.223	0.045	-0.231	-0.09
	significance	0	0.149	0.086	0.733	0.075	0.495

* Significant at the 0.05 level (two-tailed). ** Significant correlation at the 0.01 level (two-tailed).

3.1.2. Two-Dimensional Scale Combination

In the two-dimensional scale combination of length (L) and width (D), the top and bottom interfaces are controlled by L and D, respectively. The area of the interface is represented by L*D, while the aspect ratio of the interface is represented by L/D. Table 4 shows a strong positive correlation between L/D and length perception (P=0.854). This means that the larger the L/D value, the longer people perceive the distance of the street space. On the other hand, there is a highly negative correlation between L/D and the perception of stability (P=-0.801). This indicates that as the L/D value increases, people perceive less stability in the street space.

In the two-dimensional scale combination of length (L) and height (H), L and H control the side interface of the underground commercial street. The area of the side interface is represented by L*H, while L/H represents the length-height ratio of the side interface. As shown in Table 4, there is a strong correlation between L-H and length perception (P=0.763). This suggests that the larger the L-H value, the longer the distance of the street space is perceived to be.

In the two-dimensional scale combination of width (D) and height (H), D and H control the positive interface of the underground commercial street space. The area of the positive interface is represented by D*H, while D/H represents the width-to-height ratio of the positive interface. According to Table 4, D/H has significant correlation coefficients (P=0.960; P=-0.941; P=0.849) for width, height, and perception of openness. This means that as the D/H value increases, the perceived width of the street space becomes longer, the height becomes lower, and the perception of openness of the street space increases. D/H has a stronger correlation with spatial perception than the one-dimensional scale combinations.

Table 4. Table of correlation coefficients between two-dimensional scale variable combinations and cognitive evaluation.

		length cognition	width cognition	height cognition	openness cognition	stable cognition	comfort cognition
L*D	Pearson	0.062	0.672**	-0.546**	0.730**	0.465**	0.449**
	significance	0.638	0	0	0	0	0
L/D	Pearson	0.854**	0.784**	0.789**	0.745**	-.801**	-0.679**
	significance	0	0	0	0	0	0
L*H	Pearson	0.763**	-0.299*	0.432**	-0.126	-0.227	-0.114
	significance	0	0.02	0.001	0.336	0.081	0.386
L/H	Pearson	0.566	0.001	-0.078	0.207	-0.145	-0.028
	significance	0	0.996	0.553	0.113	0.269	0.829
D*H	Pearson	-0.309*	0.741**	-0.576**	0.626**	0.674**	0.505**
	significance	0.016	0	0	0	0	0
D/H	Pearson	-0.461**	0.960**	-0.941**	0.849**	0.622**	0.489**
	significance	0	0	0	0	0	0

* Significant at the 0.05 level (two-tailed). ** Significant correlation at the 0.01 level (two-tailed).

3.1.3. Summary Table of Factors of Maximum Relevance Scale Combinations

By analyzing the correlation between one-dimensional and two-dimensional scale combinations and the six spatial perceptions, this paper summarizes the scales with the highest correlation factor with individual perceptions, as shown in Table 5. The findings reveal that the two-dimensional scale combinations correlate more strongly with overall spatial perception compared to the 1D scales. Specifically, the L/D scale combination demonstrates a high correlation with length perception (P=0.854), stable perception (P=-0.801), and a significant correlation with comfort perception (P=-0.679). On the other hand, the D/H scale combination shows a high correlation with width perception (P=0.960), height perception (P=0.941), and openness perception (P=0.849). These results indicate that the combination of two-dimensional scales, particularly L/D and D/H, has a more significant impact on overall spatial perception.

Table 5. Summary of maximum relevance scale combination factors.

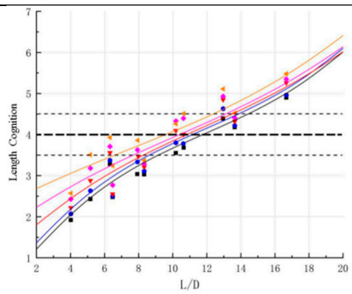
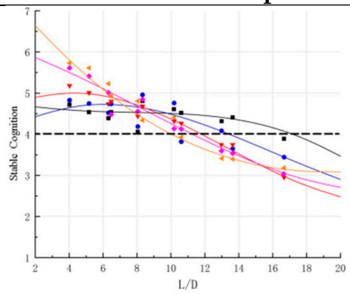
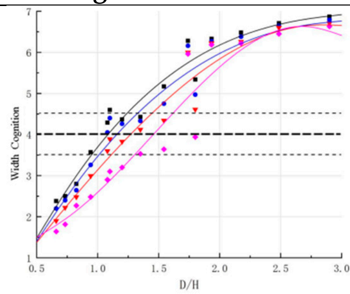
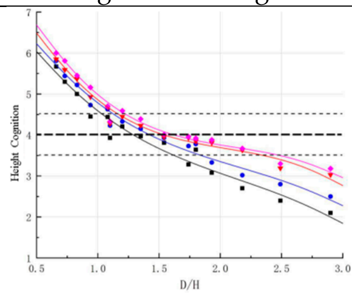
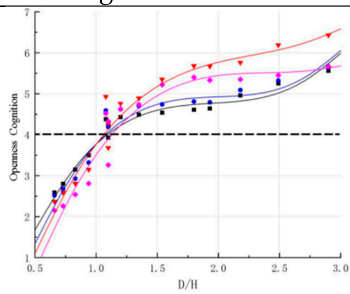
	length cognition	width cognition	height cognition	openness cognition	stable cognition	comfort cognition
Maximum Relevance scale factor	L/D	D/H	D/H	D/H	L/D	L/D
Pearson	0.854**	0.960**	0.941**	0.849**	-0.801**	-0.679**

* Significant at the 0.05 level (two-tailed). ** Significant correlation at the 0.01 level (two-tailed).

3.2. Regression Analysis of Maximum Correlation Scale Factors and Spatial Perception

The paper investigates the influence of two scale combinations, aspect ratio L/D and aspect ratio D/H, which are considered the most influential. In order to determine the appropriate range, the study examines the relationship between each scale factor and its highly correlated perception. The analysis uses SPSS, where the three two-dimensional scale combinations with the highest correlation coefficients are regressed against their corresponding highly correlated perceptions, and fitting curves are plotted. Since the independent variable consists of two scale elements, it is possible to categorize it based on one of the remaining scale elements, resulting in multiple fitted curves on the graph. The corresponding range of appropriateness under the scale difference can be derived by applying the judgment law of appropriate perception states. The derived range of appropriateness is presented in Table 6 (a-e).

Table 6. Maximum correlation scale factors and spatial cognition regression analyses.

Maximum correlation scale factors and spatial cognition regression		
 (a) Aspect Ratio L/D and cognition of length	 (b)Aspect Ratio L/D and cognition of stable	 (c)Aspect Ratio D/H and cognition of width
 (d)Aspect Ratio D/H and cognition of height	 (e)Aspect Ratio D/H and cognition of openness	

Based on the judgment law of the appropriate perception state and combined with the fitting curve diagram, calculations were made to determine the L/D ranges when the length perception and the stable perception reached the appropriate state individually, as well as the L/D range when both of them reached the appropriate state together. Additionally, the overall appropriateness range at different heights was also determined. Table 7 presents these findings. For a height of 3m, the appropriate range of L/D was found to be 9.2-14.3. Similarly, for a height of 3.5m, the appropriate range of L/D was 8.5-13.0. The appropriate range for a height of 4.0m was 8.3-11.6, for a height of 4.5m it was 7.6-11.2, and for a height of 5.0m it was 7.0-10.0. By examining the intersection of these ranges, it was discovered that the L/D range of 9.0-10.0 was achieved when both types of perception reached the appropriate state across all height ranges. Therefore, the final determined L/D range is 9.2-10.0.

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Table 7. Suitable range of L/D for aspect ratios.

	L/D					
	H=3.0m	**H=3.5m**	**H=4.0m**	**H=4.5m**	**H=5.0m**	**H=3.0m**
length range	9.2-14.3	8.5-14.0	8.3-13.5	7.6-13.2	7.0-12.5	9.2-14.3
stable range	4.0-17.1	4.0-13.5	4.0-11.6	4.0-11.2	4.0-10.0	4.0-17.1
length/stable range	9.2-14.3	8.5-13.0	8.3-11.6	7.6-11.2	7.0-10.0	9.2-14.3
the overall range	9.2-10.0					

Based on the judgment law of appropriate perception state and combined with the fitting curve diagram, the D/H range is calculated when width perception, height perception, and openness perception reach the appropriate state respectively under different lengths. Table 8 shows the calculated D/H range when all three reach the appropriate state together, as well as the overall appropriate range. For a length of 35m, the appropriate range of D/H is 1.1-1.3. For a length of 45m, the appropriate range of D/H is 1.1-1.4. For a length of 55m, the appropriate range of D/H is 1.2-1.5. For a length of 70m, the appropriate range of D/H is 1.2-1.6. The intersection of these ranges forms the range of D/H when the three kinds of perception reach the appropriate state together for all lengths, which is 1.2-1.3.

Table 8. Suitable range of aspect ratio D/H.

	D/H					
	H=3.0m	**H=3.5m**	**H=4.0m**	**H=4.5m**	**H=5.0m**	**H=3.0m**
width range	0.9-1.3	1.0-1.4	1.1-1.4	1.2-1.6	0.9-1.3	1.0-1.4
height range	1.0-1.6	1.1-1.8	1.2-2.3	1.3-2.4	1.0-1.6	1.1-1.8
openness range	1.1-2.9	1.1-2.9	1.1-2.9	1.2-2.9	1.1-2.9	1.1-2.9
width/height/openness range	1.1-1.3	1.1-1.4	1.2-1.5	1.2-1.6	1.1-1.3	1.1-1.4
the overall suitable range	1.2-1.3					

Through correlation analysis of one-dimensional and two-dimensional scale combinations, as well as spatial perception, it was found that the two-dimensional scale combination has a stronger correlation with six types of perception. Specifically, the length/width ratio (L/D) and width/height ratio (D/H) show the highest correlation coefficient with spatial perception. The appropriate range for the length/width ratio (L/D) gradually decreases with an increase in heigh. In contrast, the appropriate range for the width/height ratio (D/H) gradually increases with an increase in length. Moreover, as the length increases, its appropriate range also gradually increases.

3.3. Coverage Analysis of the Appropriate Scope of Two-Dimensional Scale Combination

This paper analyzes the range of appropriate two-dimensional scale combinations in terms of coverage, specifically focusing on their applicability to different scale combinations of underground commercial streets. To enhance the feasibility of the study, the perception trend of two scale elements is examined by varying another scale element. The variable length (L) allows for a comprehensive exploration of three-dimensional scale combinations. By determining the appropriate range of aspect ratio (L/D) for different heights (H), the corresponding lengths (L) for three widths (D) of underground commercial streets within this range can be identified. The perception appropriateness within this range reflects the coverage of the two-dimensional scale combinations. If a majority of the length perceptions and stable perceptions fall within the appropriate range of L/D, it indicates good coverage. If some of the length perceptions and stable perceptions are within the appropriate range of L/D, it suggests general coverage. However, if the length and stable perceptions do not fall within the appropriate range of L/D, it indicates a lack of coverage.

Firstly, the appropriate lengths (L) corresponding to the three widths (D) were obtained based on the appropriate range of aspect ratios (L/D) for five different heights (H). This information is presented in Table 9. Subsequently, regression analysis was performed in SPSS, considering the scale

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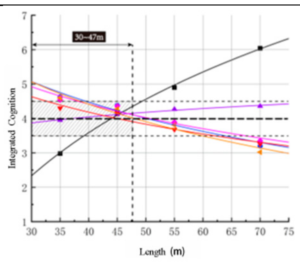
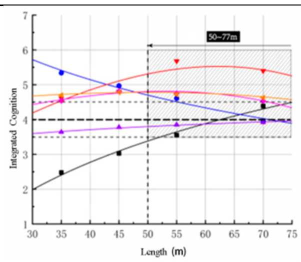
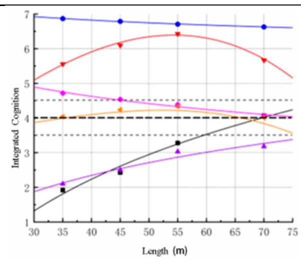
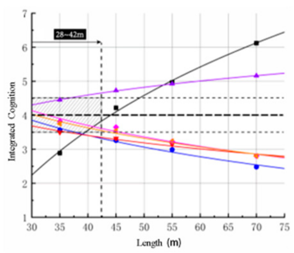
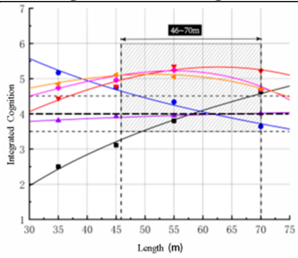
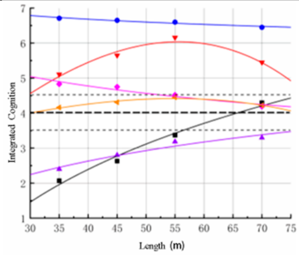
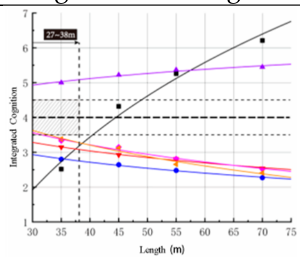
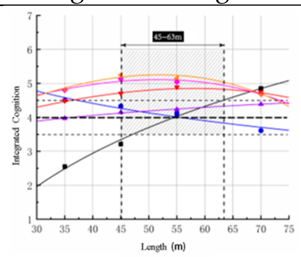
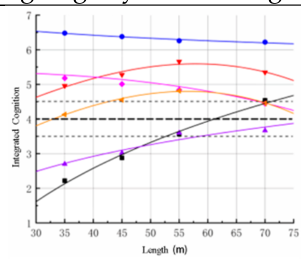
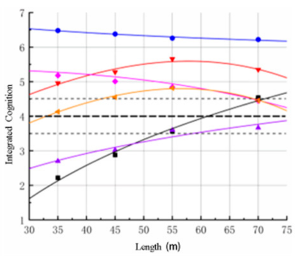
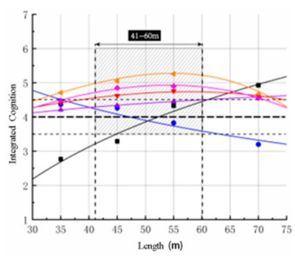
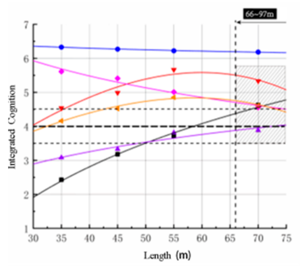
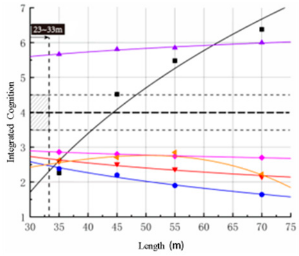
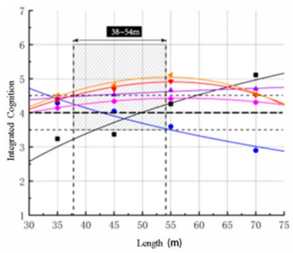
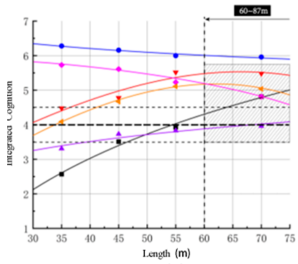
combination changes and the quantified perception evaluation data from Experiment 1. The fitting curves for the six kinds of spatial perception were obtained and integrated into a single graph, creating an overall perception change graph. To further explore the coverage of different three-dimensional scale combination streets by the two-dimensional scale combination fit range, the overall perception change map was combined with the obtained length (L) fit range. This combined information is shown in Table 10.

Table 9. L suitable range derived from L/D suitable range.

	L		
	D=3.3m	**D=5.4m**	**D=8.7m**
H=3.0m	30-47	50-77	80-124
H=3.5m	28-42	46-70	73-113
H=4.0m	27-38	45-63	72-100
H=4.5m	25-37	41-60	66-97
H=5.0m	23-33	38-54	60-87

Table 10. Graph of overall cognitive curve corresponding to suitable length.

	3.3m width	5.4m width	8.7m width
3.0m height	 general coverage	 good coverage	 going beyond coverage
3.5m height	 general coverage	 good coverage	 going beyond coverage
4.0m height	 no coverage	 good coverage	 going beyond coverage
4.5m height	 no coverage	 good coverage	 general coverage

5.0m height			
	no coverage	good coverage	general coverage

—■— length cognition; —●— width cognition; —▲— height cognition; —▼— openness cognition; —◆— stable cognition; —◄— comfort cognition

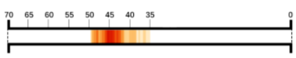
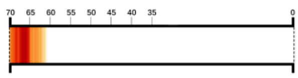
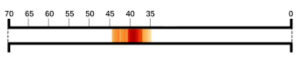
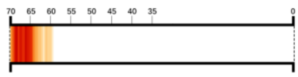
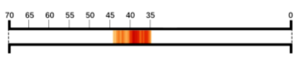
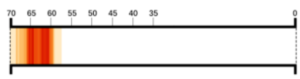
As shown in Table 11, the underground commercial street with a width (D) of 3.3 m has appropriate lengths for heights of 3 m and 3.5 m, resulting in general coverage. Similarly, in the underground commercial street with a width (D) of 5.4 m, most of the length and stable perceptions are appropriate within the obtained appropriate lengths, indicating good coverage of the length-to-width ratio (L/D). On the other hand, for heights of 4.5 m and 4 m, some of the lengths and stable perceptions can reach the appropriate state with general coverage. While some streets have lengths exceeding the experimental length setting range, most streets achieve appropriate perception. Therefore, the two-dimensional scale combination L/D effectively covers most of the street space with different three-dimensional scale elements. Determing of experimental length values through statistical analysis of previous research data adds practical significance to the findings.

3.4. Analysis of the Selection Range of Appropriate Length of Three-Dimensional Scale Combination

In order to comprehensively explore the spatial scale, this paper conducted an experiment called the three-dimensional scale combination-appropriate length selection experiment. The experiment aimed to determine the appropriate length selection range for underground commercial streets with different width and height values. By doing so, the study identified the appropriate range of three-dimensional scale combinations and their corresponding change rules.

In this study, a total of 600 selection points were recorded by 40 subjects in 15 virtual underground commercial streets. The selection points were determined based on the acceptable street lengths for the subjects, and the appropriate length ranges were derived from the lengths chosen by all subjects. The author created a plan view of each street scenario to represent the aggregation of length values visually. The author marked the street length range of 35-70 m, which was determined through actual research, and overlaid the selected appropriate length values from all subjects onto the graph. The darkness of the colors in the graph indicates the number of people who chose the respective lengths, with darker colors representing a higher cumulative number of people. The colored ranges on the graph represent the appropriate length ranges, while the darker parts indicate the most appropriate length ranges (see Table 11). Finally, a summary table presenting the appropriate and optimal length ranges will be generated, as shown in Table 12.

Table 11. Overlay with suitable length selection.

	3.3m width	5.4m width	8.7m width
3.0m height			
3.5m height			
4.0m height			

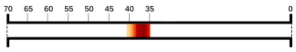
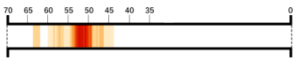
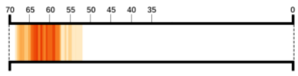
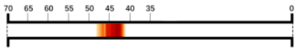
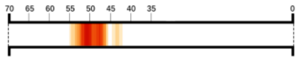
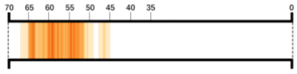
4.5m height			
5.0m height			

Table 12. Summary table of suitable length range and most suitable length range.

	3.3m width	5.4m width	8.7m width
3.0m height	(35-49);(43-46)	(57-70);(62-66)	(62-70);(66-70)
3.5m height	(35-44);(37-41)	(52-68);(58-63)	(60-70);(64-70)
4.0m height	(35-44);(35-40)	(45-65);(50-55)	(58-70);(60-66)
4.5m height	(35-40);(35-38)	(43-63);(49-53)	(51-68);(57-65)
5.0m height	(42-48);(43-46)	(42-55);(46-52)	(45-67);(52-65)

3.5. Comparison Analysis of Appropriate Length Range

The length appropriate range was determined through two experiments: one using the L/D appropriate range and the other using a combination of three-dimensional scales. The experimental data from Tables 10 and 13 were used to control the interval range. The overlapping range of the two groups of experiments is shown in Figure 5. After removing the interval range that does not intersect at all, the best length appropriate range was obtained, resulting in a total of eight groups, as shown in Table 13.

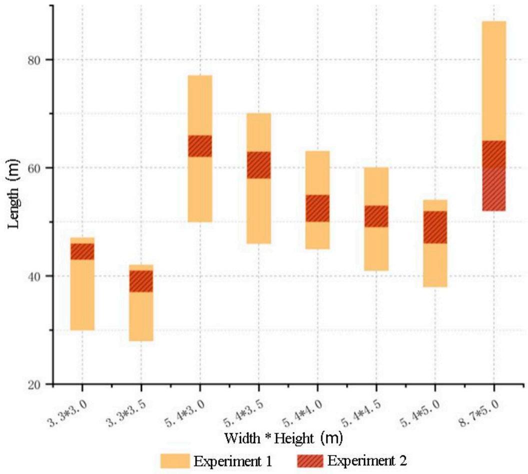


Figure 5. Comparison of range intervals.

Table 13. Summary of optimum length ranges.

NO.	W*H	Length range
1	3.3*3.0	(43-46)
2	3.3*3.5	(37-41)
3	5.4*4.0	(50-55)
4	5.4*5.0	(46-52)
5	5.4*3.0	(62-66)
6	5.4*3.5	(58-63)
7	5.4*4.5	(49-53)
8	8.7*5.0	(60-65)

4. Discussions

4.1. Research Innovation

Research on enhancing the quality of street spaces has traditionally emphasized street spatial scale, a crucial aspect even within the virtual realm of platforms like Google Street View. Prior studies by Kashiwagi[28] and Matsumoto [29] have illustrated the close relationship between physical factors such as street aspect ratio and spatial perception through perceptual models. Similarly, Liu (2020) utilized street length and width as research indices to investigate their impact on pedestrian travel[30]. However, existing literature predominantly examines scale elements along a single dimension within spatial scale analysis. Departing from this approach, the current study extends the analysis from a one-dimensional to a three-dimensional scale, yielding more comprehensive and direct insights. By analyzing the significant influence of spatial scale on perception evaluation, enhanced recommendations for improving street spatial quality are provided.

In regards to the measurement of street cognition data, this study also constructed a virtual reality platform for behavioural recording and cognitive evaluation concerning Cipresso [32], which was previously primarily applied in clinical research[33], where subjects were able to achieve awareness and comparison of multiple scenarios in a virtual scenario, and which also allowed for real-time recording of the subjects' behavioural data. The study learnt from Ge's method of investigating street scene environments[31], where cognitive appraisal was measured by presenting the street scenes to the subjects as adjective pairs for scoring. Unlike previous studies, the study conducted two experiments simultaneously to obtain cognitive evaluation data and appropriate length selection data, which is conducive to validating the final results.

In the research on the appropriate range of street length, Xiao Y showed that the appropriate length of above-ground streets is 249 m. In this study, underground streets were used as the object of research, and the study concluded that the length of underground streets ranges from 43 to 66 m, which makes up for the research gap in the underground area[34]. Yu Z found that the appropriate ratio of street width and height is 1~2, which is basically in line with the value of 1.2~1.3 of the width-to-height ratio in this experiment when researching the interface morphology of streets[36] . It is worth noting that Zhan L et al. (2019) used psycho-cognitive evaluation to analyse the appropriate scale of the space and obtain the appropriate values under different width-to-height, length-to-height and width-to-length scale indicators[37]. However, it needed an analysis of the impact of one-dimensional and three-dimensional scale data. Ultimately, the data obtained could only be based on the two-dimensional scale of the appropriate scale evaluation recommendations.

In contrast, the methodology of the present study can be used through one scale indicator. The method of this study can infer the range values of the remaining two scales through one scale indicator. Different from the previous study, the above study considered that when the width is about 5.4, the appropriate length is about 55m, but the results of this study show that when the width is 5.4m, with the change of the height, the length value can reach the appropriate requirement within the range of 46~66m. Therefore, when researching the appropriate scale of street space, the three dimensions should be fully considered, and the impact of changes in each dimension on the quality of street space should be observed.

4.2. Limitations and Future Directions

This study uses a virtual reality modelling platform to model the experiment, but it has yet to exploit its full advantage - realism fully. The experiment only takes spatial scale indicators as the object of study, and the constructed scene itself is relatively simple, with some differences from natural street scenes, which may only allow subjects to immerse themselves in the environment for evaluation partially.

At the level of spatial cognitive evaluation, although the study covered all the indicators related to spatial scale as much as possible and filtered them, adjectives such as beautiful, lively, engaging, etc., which are highly related to the quality of street space, could not be used as the evaluation

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indicators to measure the spatial scale evaluation. The study only focused on the factors that are influencing the spatial scale.

Therefore, in future research on street space appropriateness, we can add more research objects as much as possible, improve the experimental model, increase the fidelity of the model, and take into account the visual, acoustic, and thermal comfort environments to record the state of the research objects from more dimensions and collect multimodal perceptual evaluation data to conduct interactive analyses to validate the accuracy of the experiments.

5. Conclusions

Through the analysis and verification of perception evaluation experiments combining one-dimensional and two-dimensional scales, as well as appropriate length selection experiments combining three-dimensional scales, data was obtained on the optimal appropriate length range and scale combination for underground commercial streets. Through the one-dimensional and two-dimensional scale combination of cognitive evaluation experiments and three-dimensional scale combination of appropriate length selection experiments of data testing and analysis, finally obtain the best underground commercial street with a appropriate length range and scale combination of data in the width of 3.3 metres of the underground commercial street, when the experimental height of the value of dimensions of 3 metres, the appropriate length range of about 43-46 metres. When the experimental height takes the value of 3.5 metres, the appropriate length range is about 37-41 metres; in the underground commercial street with a width of 5.4 metres, when the experimental height takes the value of 3.0 metres, the appropriate length range is about 62-66 metres, and when the experimental height takes the value of 3.5 metres, the appropriate length range is about 58-63 metres. When the experimental height is 4.0 metres, the appropriate length range is about 49-53 metres. When the experimental height takes the value of 5.0 metres, the most appropriate length range is about 46-52 metres; compared with other widths, the spatial cognition of the underground commercial street with a width of about 5.4 metres generally reaches a appropriate state within the appropriate length range, indicating that this value is used as the recommended data for the width of the underground commercial street; in the underground commercial street with a width of 8.7 metres, the experimental height takes the value of 5 metres, and the most appropriate length range is about 60-65 metres. 65 metres. Under the above eight groups of three-dimensional scale combinations, the overall cognition of the underground commercial street is the most appropriate, which can bring the most comfortable feeling to people.

The relationship between the appropriate width-to-height ratio of an underground commercial street and the overall perception of its space can be summarized as follows: a more appropriate ratio will result in a higher overall perception of appropriateness and a more extensive range of appropriate length options. The variation pattern of the appropriate range of three-dimensional scale combinations is as follows: when the width is 3.3 meters, the appropriate length range initially decreases and then increases with the increase in height; when the width is 5.4 meters, the appropriate length range gradually decreases with the increase in height; when the width is 8.7 meters, the appropriate length range also gradually decreases with the increase in height.

Appendix A

This paper utilizes high-frequency data from underground commercial streets to create a total of 60 street models. These models are formed by combining five different heights (H), three different widths (D), and four different lengths (L) in both one-dimensional and two-dimensional scales. The values of the variables for the one-dimensional and two-dimensional scales are presented in Table A1.

Table A1. One and two dimensional scale combination variables taking values.

	NO.	H(m)	D(m)	L(m)	L*D	L/D	L*H	L/H	D*H	D/H
Scene I	M1	3	3.3	35	115.5	10.6	105	11.7	9.9	1.1
	M2	3	3.3	45	148.5	13.6	135	15	9.9	1.1
	M3	3	3.3	55	181.5	16.7	165	18.3	9.9	1.1
	M4	3	3.3	70	231	21.2	210	23.3	9.9	1.1
	M5	3	5.4	35	189	6.5	105	11.7	16.2	1.8
	M6	3	5.4	45	243	8.3	135	15	16.2	1.8
	M7	3	5.4	55	297	10.2	165	18.3	16.2	1.8
	M8	3	5.4	70	378	13	210	23.3	16.2	1.8
	M9	3	8.7	35	304.5	4	105	11.7	26.1	2.9
	M10	3	8.7	45	391.5	5.2	135	15	26.1	2.9
	M11	3	8.7	55	478.5	6.3	165	18.3	26.1	2.9
	M12	3	8.7	70	609	8	210	23.3	26.1	2.9
Scene II	M13	3.5	3.3	35	115.5	10.6	122.5	10	11.6	0.9
	M14	3.5	3.3	45	148.5	13.6	157.5	12.9	11.6	0.9
	M15	3.5	3.3	55	181.5	16.7	192.5	15.7	11.6	0.9
	M16	3.5	3.3	70	231	21.2	245	20	11.6	0.9
	M17	3.5	5.4	35	189	6.5	122.5	10	18.9	1.5
	M18	3.5	5.4	45	243	8.3	157.5	12.9	18.9	1.5
	M19	3.5	5.4	55	297	10.2	192.5	15.7	18.9	1.5
	M20	3.5	5.4	70	378	13	245	20	18.9	1.5
	M21	3.5	8.7	35	304.5	4	122.5	10	30.5	2.5
	M22	3.5	8.7	45	391.5	5.2	157.5	12.9	30.5	2.5
	M23	3.5	8.7	55	478.5	6.3	192.5	15.7	30.5	2.5
	M24	3.5	8.7	70	609	8	245	20	30.5	2.5
Scene III	M25	4	3.3	35	115.5	10.6	140	8.8	13.2	0.8
	M26	4	3.3	45	148.5	13.6	180	11.3	13.2	0.8
	M27	4	3.3	55	181.5	16.7	220	13.8	13.2	0.8
	M28	4	3.3	70	231	21.2	280	17.5	13.2	0.8
	M29	4	5.4	35	189	6.5	140	8.8	21.6	1.4
	M30	4	5.4	45	243	8.3	180	11.3	21.6	1.4
	M31	4	5.4	4	5.4	10.2	220	13.8	21.6	1.4
	M32	4	5.4	70	378	13	280	17.5	21.6	1.4
	M33	4	8.7	35	304.5	4	140	8.8	34.8	2.2
	M34	4	8.7	45	391.5	5.2	180	11.3	34.8	2.2
	M35	4	8.7	55	478.5	6.3	220	13.8	34.8	2.2
	M36	4	8.7	70	609	8	280	17.5	34.8	2.2
Scene IV	M37	4.5	3.3	35	115.5	10.6	157.5	7.8	14.9	0.7
	M38	4.5	3.3	45	148.5	13.6	202.5	10	14.9	0.7
	M39	4.5	3.3	55	181.5	16.7	247.5	12.2	14.9	0.7
	M40	4.5	3.3	70	231	21.2	315	15.6	14.9	0.7
	M41	4.5	5.4	35	189	6.5	157.5	7.8	24.3	1.2
	M42	4.5	5.4	45	243	8.3	202.5	10	24.3	1.2
	M43	4.5	5.4	55	297	10.2	247.5	12.2	24.3	1.2
	M44	4.5	5.4	70	378	13	315	15.6	24.3	1.2
	M45	4.5	8.7	35	304.5	4	157.5	7.8	39.2	1.9
	M46	4.5	8.7	45	391.5	5.2	202.5	10	39.2	1.9
	M47	4.5	8.7	55	478.5	6.3	247.5	12.2	39.2	1.9
	M48	4.5	8.7	70	609	8	315	15.6	39.2	1.9
Scene V	M49	5	3.3	35	115.5	10.6	175	7	16.5	0.7
	M50	5	3.3	45	148.5	13.6	225	9	16.5	0.7

M51	5	3.3	55	181.5	16.7	275	11	16.5	0.7
M52	5	3.3	70	231	21.2	350	14	16.5	0.7
M53	5	5.4	35	189	6.5	175	7	27	1.1
M54	5	5.4	45	243	8.3	225	9	27	1.1
M55	5	5.4	55	297	10.2	275	11	27	1.1
M56	5	5.4	70	378	13	350	14	27	1.1
M57	5	8.7	35	304.5	4	175	7	43.5	1.7
M58	5	8.7	45	391.5	5.2	225	9	43.5	1.7
M59	5	8.7	55	478.5	6.3	275	11	43.5	1.7
M60	5	8.7	70	609	8	350	14	43.5	1.7

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