


## Article

# The Effects of Ambient Illumination, Color Combination, Sign Height, and Observation Angle on the Legibility of Wayfinding Signs in Metro Stations

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Received: 9 April 2020; Accepted: 15 May 2020; Published: 18 May 2020



**Abstract:** Well-designed wayfinding signs play an important role in improving the service level of metro stations, ensuring the safety of passengers in evacuation, and promoting the sustainable development of public transport. This study explored the effects of ambient illumination, color combination, sign height, and observation angle on wayfinding signs' legibility in metro stations. In the experiment, simulated metro-wayfinding signs were made to test legibility. As designed, the legibility was measured based on the following independent variables: two levels of ambient illumination (70 lux and 273 lux), two target/background color combinations (achromatic-white target on black background, chromatic-yellow target on black background), two sign heights (1.5 m and 2 m), and three observation angles (0°, 45°, 70°). The results showed that brighter ambient illumination provided passengers with higher legibility. Achromatic color combination was more legible than chromatic color combination, but not significantly. Different types of signs, set at different height, did not directly affect legibility. Observation angle had significant effects on legibility. Visibility catchment area of wayfinding signs was like an ellipse, with its short axis nearly equal to the legibility distance of the sign at 0 degrees. The findings will facilitate the layout and setting location of wayfinding signs in metro stations and improve the level of wayfinding service.

**Keywords:** wayfinding signs; legibility; metro station; ambient illumination; observation angle

## 1. Introduction

The use of underground facilities is tied to the sustainability of an urban area because it can alter the basis for economic conditions in an urban area by providing a better transportation and utility infrastructure that would be impossible to construct on the surface [1]. The metro bears a growing number of public transport passengers in Chinese cities, because of its large capacity, fast speed, and high punctuality. By the end of 2019, there were 181 metro lines in operation in 32 Chinese cities, with a total length of 6730.27 km [2]. The number of passengers on the Shanghai metro exceeded 12 million on a single day in 2019 [2]. Among massive passenger flow in peak hours, some passengers tend to slow down or even stop to look for directions or location information, causing the latter flow of passengers to block. Yu found that 62% of the people in Shanghai South Railway Station had difficulty in finding their way, and 34% had trouble getting lost [3]. The safety of passengers inside the stations will not be guaranteed or passengers may experience increased blood pressure, headaches, feelings of desperation, and weariness as a result of losing their way [4]. Bennett has claimed that it's no use expanding the underground network and increasing train frequency without improving passenger

circulation and flow at the busy stations' in his book [5]. Therefore, when the development of urban metro has reached a certain degree, the improvement of passenger mobility efficiency in the main hubs of the network becomes a more critical factor than the expansion of the network and the shortening of train intervals [6]. Recently, many scholars have established micro-simulation models of pedestrians in metro stations, such as Mobile Benefit Model, Cellular Automata Model, and Social Force Model, to simulate the walking process of pedestrians in the station. However, the existing simulation system cannot be directly applied to the evaluation of urban metro hubs [6]. Passengers will choose the direction and speed of the next step not only according to the shape of the building space, the position of the obstacle, and the position of other passengers, but their choice will be affected by the signs in the station. For example, passengers will be guided in the visibility catchment area of the sign and their speed decreases when they observe the signs [7], but will choose to follow the crowd when not in the area. Therefore, the study on the visibility catchment areas of different types of signs in metro stations can provide a basis for a more accurate pedestrian simulation system.

The three basic pillars of sustainability are generally recognized to be environment, economy, and society [1]. If a passenger is in a long passageway without any signs, he or she cannot be sure that they are following the path they wanted. They may return to the passageway entrance to confirm the directional information, which may produce opposite traffic flow, increasing the likelihood of traffic congestion. On the contrary, if there are too many signs, reading messages on the signs will affect their walking speed and increase the economic cost of the station. Most signs in metro stations use lightboxes. According to the legibility distance of signs, the quantities and locations of signs can be reasonably selected, in order to eliminate the anxiety of passengers in the long passageways; minimize economic cost; and make the signage system meet the needs of sustainable development such as humanization, energy conservation, and environmental protection [3]. The perception of a city by passengers from other cities and the international community may be based on the transportation system. If the metro station can provide a humanized and convenient visual guidance system, it will be of great help to improve the social sustainability of a city. A well-designed wayfinding system will facilitate the safety of walking and enhance the efficiency of the operation service of metro stations from a systematic level [8]. In assurance of the efficient and robust operation of the metro system, the necessity of wayfinding signs' legibility should be emphasized to provide practical reference for their optimal board layout, setting height and location, and environmental illumination.

Peponis and Zimring [9] have described wayfinding as the ability to reach an objective in a short time without experiencing fear and stress. In the metro station, passengers need to reach their destination (correct platform for inbound and transfer streamline, and correct exit for outbound streamline) in a short time. A successful wayfinding system will not only reduce the complexity within a building and guide people to their destination, but also enhance the safety of walking in the case of emergency condition or massive passenger flow in peak hours [10]. Previous studies on indoor wayfinding system were mostly carried out in hospitals, shopping malls, airports, and other places. However, most of the metro stations are built underground, lacking natural lighting, with their environment being relatively dark, and a large number of people can be gathered in a short time. Therefore, the environment of the metro station is quite different from the above places, evoking the necessity of research on wayfinding signs setting in metro stations. Jeon and Hong [11] carried out a study on the wayfinding in the metro station under fire smoke. They found that when the distance between the phosphorescent signs on the ground is less than a person's step, it will greatly reduce the evacuation time [11]. Frank and Akkelies [12] explored the potential use of the space syntax methodology for evaluating user wayfinding, orientation, and visibility, but they only use the physical connection of space, without considering the role of the signage system in space visibility. First, the sign can connect two areas that are not directly visible. Second, in a long corridor, even if the vision is unobstructed, the function of the area at the end of the corridor may not be clearly identified. Therefore, it is of great value to study the legibility distance of a signage system. If a pedestrian is

within the legibility distance, the function of an area can be known according to the message of the sign, even if the area is not directly connected by the sightline.

Legibility is a commonly used ergonomic criterion for display evaluation [13–18]. Recognition and legibility distances are indicative of a sign's visual performance [19], and they are used as the dependent variable in experiments of traffic signs in many articles [20,21]. Recent works on text legibility are mostly focused on screens at a short distance with subject rating scores or reading time. Participants sat in front of a computer and identified the text legibility. The size of the sign and the distance between the sign and the participant vary in the same proportion, but the size of the participant and the perception of the brightness of different distances cannot be changed. Body movements and even small changes in location reflect correct and realistic changes in perspective and view. Therefore, our experiment was carried out using the real size of existing signs in Shanghai metro stations, which is of more practical value. Moreover, important factors that may influence wayfinding signs' legibility in metro station were not studied until recently. This study aims to investigate the effects of sign design and station environment, such as ambient illumination, color combination, sign height, and observation angle, as well as visibility catchment area, on sign legibility. Considering that studies on the legibility of signs in the metro station environment are few, this study is valuable.

Ambient illumination may significantly affect the visual performance of metro signs. Knez and Kers [22] have indicated that indoor lighting directly affects users' emotions, memory, perceptual-orientation, and problem-solving abilities. Recent laboratory-based research examining legibility at a glance has shown that the amount of on-screen display time needed to identify a word was reduced globally under conditions of high ambient illumination [23]. Hidayetoglu et al. [24] found that, parallel to the increase in the level of brightness, the perceptual evaluations of the participants increased in a positive direction. However, in Hidayetoglu et al.'s experiment [24], the value seen as high was 130 lux, which is lower than that in real metro stations. Liu's study showed that, for phosphorus signage, the mean visual distance with illumination (about 47 lux) was greater than that without illumination (about 0 lux) [25], whose illumination value in the experiment was also low. As the ambient illumination value increased, so did legibility, but the extent to which it affects legibility still needs to be studied further under the metro station environment.

Color combination influences legibility [26,27] and visual search performance [28]. Huang [29] suggested that achromatic color was the most effective background chromaticity with lower reading time and had a higher preference rating through participants. While Lin [30] found a somewhat greater grand-mean visual preference for chromatic text (67.41%) than for achromatic text (62.36%), the difference did not reach statistical significance. Therefore, the combination of colors has a certain influence on the legibility. Inbound and outbound streamline signs are of different colors in most metro stations in China. However, there are relatively few experiments that were carried out in the metro station environment, so it is of a certain value to consider the influence of color combination on legibility, based on the metro station environment.

The studies about the influence of sign height on the legibility are few. Yu claimed that there was a certain correspondence between visual distance, setting height, and font size [3]. Liu explained through a theoretical calculation that the installation height of the sign would not affect the pedestrian's perception of the sign because of the angle of the visible field [25]. As there are few articles about the influence of sign height on legibility through experiment, this study is worthy.

The observation angle also influences legibility, thus affecting the visibility catchment area (VCA) [25,31]. The observation angle was defined as the angle subtended by the observers' line of sight to a normal line bisecting the surface of the sign [31]. The VCA of a sign was defined as the region from where it is physically possible to visually receive and discern information from the sign [31]. Xie et al. claimed that, for a sign of given size, in order to resolve the angular separation of the sign, as the observation angle increases, the maximum viewing distance must decrease, and the observation angle had a great effect on legibility distance [31]. Then, Xie et al. calculated theoretically that the VCA is a circular region. However, Liu observed that VCA was more like an ellipse through an

experiment [25]. Therefore, it is necessary and valuable to study the influence of the observation angle on legibility and corresponding VCA.

In summary, many studies have been conducted on text legibility, but not on wayfinding signs in the metro station environment. As the metro, as well as public transport, is becoming more and more important, the wayfinding efficiency in the metro stations needs to attract more attention. Metro stations are mostly built underground, lacking natural light and mostly using indoor lighting technology. The signs of inbound and outbound streamlines use different color combinations. Wallpaper signs and suspended signs are set at different heights. Passengers need to see wayfinding signs from all angles, not just in the centerline of a certain sign. Therefore, this study will explore the effects of ambient illumination, color combination, sign height, and observation angle on wayfinding signs' legibility. The results showed that brighter ambient illumination provided passengers with higher legibility. An achromatic color combination was more legible than a chromatic color combination, but not significantly. Different types of signs, set at different heights, did not directly affect legibility. Observation angle had significant effects on legibility. Visibility catchment area of wayfinding signs was like an ellipse, with its short axis nearly equal to the legibility distance of the sign seen from the centerline. Experiments on the legibility distance of different kinds of signs in Shanghai metro stations can provide a basis for the further application of space syntax. The analysis of the VCA of the signage system can provide modeling support for the pedestrian micro-simulation models to further characterize the pedestrian walking characteristics. From the results, we can choose the quantities and location of the signs reasonably, reducing the waste of resources and economic cost, improving the stations' performance service level [8], and promoting the harmonious and sustainable development of society.

The reminder of the paper is organized as follows. Section 2 introduces the details of the experiment. Section 3 presents the analysis of variance (ANOVA) results and fitting curves equation. Section 4 discusses the results through previous findings and theoretical calculations. The research is summarized in Section 5.

## 2. Methodology

### 2.1. Participants

A total of 20 participants participated in this experiment. According to "The Sixth National Census", men accounted for 51.5 percent and women accounted for 48.5% of the permanent residents in Shanghai in 2010 [32]. This is similar to the gender composition in our experiment. The participants included 11 males (mean (SD) age = 32.0 (12.2)) and 9 females (mean (SD) age = 34.2 (13.0)). Their mean (SD) age is 33.0 (12.3). The age of the participants ranges from 20 to 55. The working-age population aged 15–59 accounted for 76.3% of the total population in Shanghai [32], which is an important part of the passenger flow. All participants had 20/25 corrected visual acuity or better and normal color vision. They were recruited through electronic advertisements in campus forums and were compensated 100 RMB (≈14 USD) for their time.

### 2.2. Experiment Time and Design

Because most metro stations are built underground and in a closed environment, they lack natural lighting and all the light comes from indoor lighting. In order to simulate the indoor lighting situation, the experiment was conducted from 19:00 to 22:00 every day in January 2020. The experiment was conducted by three participants every day for a total of seven days. Four independent variables were analyzed: ambient illumination, color combination, sign height, and observation angle. The reasons and methods for their selected values are described below.

Ambient illumination: Ambient illumination values were collected using Chauvin Arnoux C.A 1110 before the experiment in real metro stations in Shanghai. Chauvin Arnoux C.A 1110 is a photometer made in France to detect environmental illumination. The locations of the five selected stations are



shown in Figure 1 and the average illumination data of the 13 sites are listed in Table 1. Jianchuan Road station is an elevated station with no transfer line. Xinzhuang station is the terminal and transfer station of line 1 and line 5. Shanghai South Railway Station is the transfer station of line 1 and line 3, and receives the passenger flow from the railway station. Xujiahui station is the transfer station of line 1, line 9, and line 11. It is located in one of the seven central business districts in Shanghai. People's Square station is the transfer station of line 1, line 2, and line 8. It is the geographical center and transportation hub of Shanghai city, integrating office, tourism, trade, and exhibition. The five selected stations include both no-transfer and transfer stations, including small passenger flows, transfer flows with other modes of transportation, and massive passenger flows in office and commercial areas. Illumination measurement points refer to the “Methods for Determination of Illumination in Public Places”, which is a Chinese standard document. Eight measurement points were selected equidistant along the centerline of the corridor. To eliminate the initial effect, the receiver was exposed for 10 min before measurement. Because the platform floor of Jianchuan Road metro station was an elevated station, the ambient illumination was the highest, which is not commonly used. The other 12 data were divided into two levels using cluster analysis, 87.3 lux (4 data) and 241.6 lux (8 data). The results of cluster analysis are shown in Figure 2. To make the experimental situation similar to real metro stations, the experimental ambient illumination was set at about 70 lux and 273 lux.

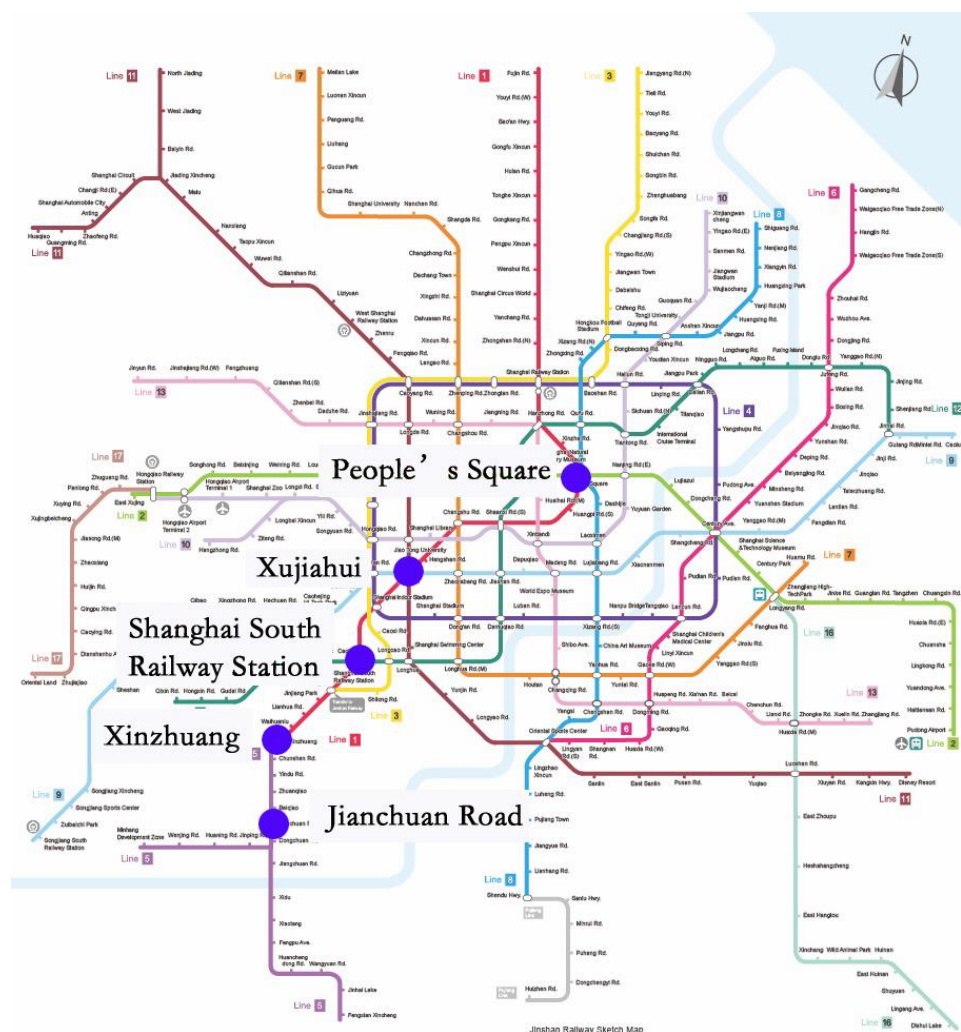
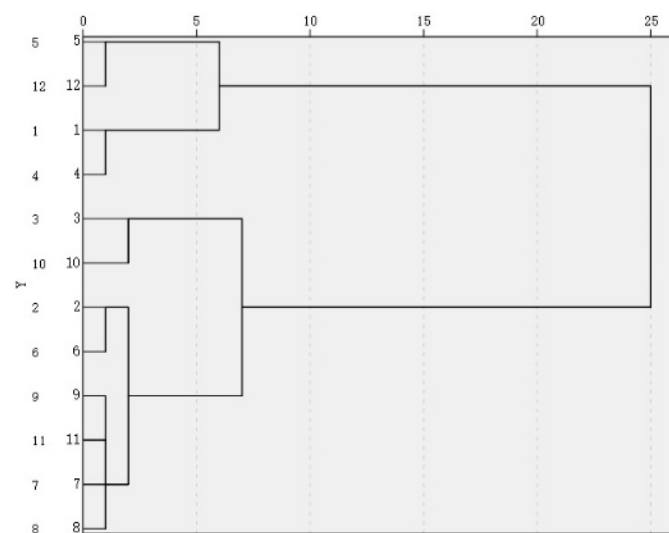


Figure 1. Locations of five real metro stations to detect illumination value.

**Table 1.** The environmental illumination in real metro stations in Shanghai.

| Station                        | Site | Max   | Min   | AVERAGE |
|--------------------------------|------|-------|-------|---------|
| Jianchuan Road                 | 1    | 220.3 | 173.5 | 192     |
|                                | 2    | 1791  | 1767  | 1778    |
| Xinzhuang                      | 1    | 236.6 | 64.4  | 138.8   |
|                                | 2    | 46.3  | 43    | 44.7    |
| Shanghai South Railway Station | 1    | 236.8 | 205.6 | 213.4   |
|                                | 2    | 295.5 | 265.6 | 282.8   |
| Xujiahui                       | 1    | 172.2 | 116.4 | 132     |
|                                | 2    | 116.2 | 103.5 | 109.9   |
|                                | 3    | 194.2 | 13    | 77      |
|                                | 3    | 107.7 | 60.8  | 88.9    |
|                                | 3    | 8.5   | 6.4   | 7.5     |
| People's Square                | 1    | 103.8 | 91.8  | 99.4    |
|                                | 2    | 340.2 | 231.8 | 278.4   |

Note: Site: 1—station hall; 2—platform; 3—transfer channel. Unit: lux.

**Figure 2.** Cluster analysis of ambient illumination in real metro stations (x\_axis: relative distance, maximum value = 25; y\_axis: sample number).

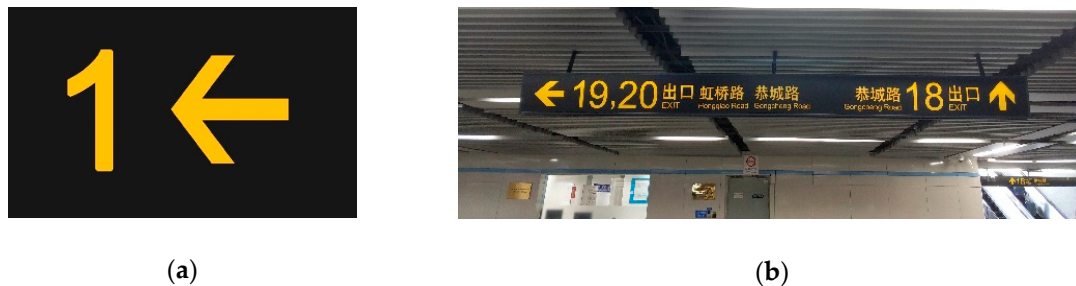
**Color combinations:** There are two kinds of color combinations in metro stations in Shanghai, white target on a black background (achromatic) for inbound streamline and yellow target on a black background (chromatic) for outbound streamline. In order to make the experimental environment similar to real metro stations, we selected the above two kinds of color combinations. They were all displayed under negative polarity (higher luminance color target shown on a lower luminance color background).

**Sign height:** Wallpaper signs and suspended signs are the most common signs in real metro stations. In metro stations in Shanghai, suspended signs are usually set at 2 m high and wallpaper signs at 1.5 m high. Sign height is defined as the distance between the bottom of the sign and the ground. Therefore, 1.5 m and 2 m were selected as the sign heights in the experiment.

**Observation angle:** In the metro stations, passengers do not always look straight from the centerline of signs. They often see it from a certain angle. In order to study the visibility catchment area of the sign, the legibility experiment was carried out from different angles: 0°, 45°, and 70°. The angle of 0° was chosen because it is the most used angle in the metro stations as passengers go forward in the centerline of the corridors. The appropriate field of vision for a person with a fixed head position is about 45 degree [33]. Therefore, we chose 45° as the second tested value. From our pre-experiment,

we found that it was hard for passengers to detect text if the angle is more than 70 degrees, and passengers tend to move toward the centerline. Therefore, 70° was chosen as the last tested value.

Different combinations of numbers and arrows were selected as experimental objects in the design of signs, as shown in Figure 3a. The numbers of exits and transfer lines are the most common factors, although the signs also contain Chinese and the corresponding English in the metro stations. The overall height of the experimental sign was 25 cm and the height of the valid target was 20 cm. The signs in the experiment were the same size as the real signs in metro stations in Shanghai. The font for the numbers was also the same as that in the real Shanghai metro stations, Times New Roman, as shown in Figure 3b.



**Figure 3.** Wayfinding signs: (a) sign design in experiment and (b) a wayfinding sign in Xujiahui metro station in Shanghai.

### 2.3. Apparatus

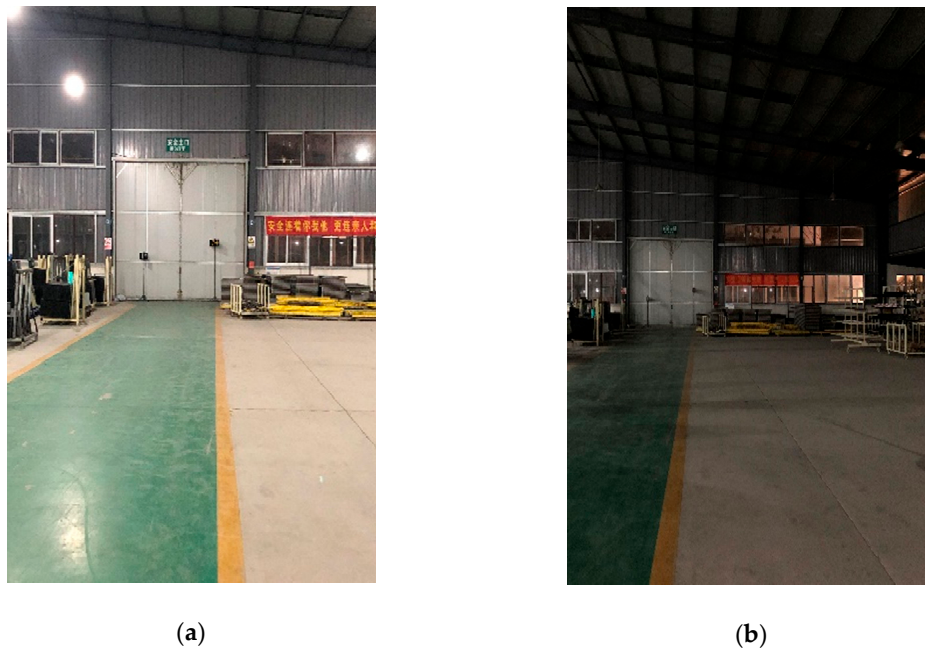
The following equipment was used in the experiment: signs containing numbers 1 to 20 and arrows in four directions, a laser rangefinder to measure the legibility distance of the sign at different angles, and a Chauvin Arnoux C.A 1110 photometer to measure illumination.

### 2.4. Workplace Conditions

The facility was difficult to change if the experiment was carried out in a real metro station. The setting height and color combination of the signs have already been fixed and cannot be changed for experimental purposes in the case of daily massive passenger flow. Thus, evaluating how combinations of various types of signs and ambient environment contribute to the legibility of traffic signs in metro stations is hard to fulfill. In the consideration of safety and not obstructing the normal operation of the station, the experiment was carried out in a factory. The tested field study provided a controlled environment, where the tested effects were investigated in a full-factorial type of experiment. The test site is 80 m long, 65 m wide, and 3.5 m high, with no obstacles existing. The maximum legibility distance of 20 cm text height was satisfied in the experiment. There are 30 LED (Light Emitting Diode) lights in total, each of which can be turned on and off to control the ambient illumination values. The internal conditions of the factory are shown in Figure 4.

### 2.5. Stimuli

In the experiment, there were two color combinations (chromatic and achromatic), two sign heights (1.5 m and 2 m), two ambient illuminations (70 lux and 273 lux), and three angles (0°, 45°, and 70°). Each participant was required to complete 24 different combinations of experimental scenarios, as shown in Table 2. It takes three minutes on average for the light to reach the maximum and stable brightness. Therefore, each participant would complete two groups of experiments in total: the first group of 12 experiments in high brightness, and then the second group of 12 experiments in low brightness. The 12 experimental conditions for each group were randomized. The numbers and arrows used in each experiment were also randomly determined by a computer program to prevent inaccurate results caused by participant's memory from the previous experiment.



**Figure 4.** Experimental site: (a) with all lights on and (b) with half of the lights off.

**Table 2.** Experimental scenarios.

| The Serial Number | Ambient Illumination | Color Combination | Sign Height | Observation Angle | Number of Participants Assigned |
|-------------------|----------------------|-------------------|-------------|-------------------|---------------------------------|
| 1                 | 273 lux              | Chromatic         | 1.5 m       | 0°                | 20                              |
| 2                 |                      |                   |             | 45°               | 20                              |
| 3                 |                      |                   |             | 70°               | 20                              |
| 4                 |                      |                   | 2 m         | 0°                | 20                              |
| 5                 |                      |                   |             | 45°               | 20                              |
| 6                 |                      |                   |             | 70°               | 20                              |
| 7                 | 70 lux               | Achromatic        | 1.5 m       | 0°                | 20                              |
| 8                 |                      |                   |             | 45°               | 20                              |
| 9                 |                      |                   |             | 70°               | 20                              |
| 10                |                      |                   | 2 m         | 0°                | 20                              |
| 11                |                      |                   |             | 45°               | 20                              |
| 12                |                      |                   |             | 70°               | 20                              |
| 13                | 70 lux               | Chromatic         | 1.5 m       | 0°                | 20                              |
| 14                |                      |                   |             | 45°               | 20                              |
| 15                |                      |                   |             | 70°               | 20                              |
| 16                |                      |                   | 2 m         | 0°                | 20                              |
| 17                |                      |                   |             | 45°               | 20                              |
| 18                |                      |                   |             | 70°               | 20                              |
| 19                | 70 lux               | Achromatic        | 1.5 m       | 0°                | 20                              |
| 20                |                      |                   |             | 45°               | 20                              |
| 21                |                      |                   |             | 70°               | 20                              |
| 22                |                      |                   | 2 m         | 0°                | 20                              |
| 23                |                      |                   |             | 45°               | 20                              |
| 24                |                      |                   |             | 70°               | 20                              |

## 2.6. Procedure

Before the experiment, the participants were informed of the experimental procedure and legibility criteria. Any questions could be asked until all the procedures were clear to them.



To begin with, all lights were turned on to keep the ambient illumination around 273 lux. Then, the experimenter placed a sign, consisting of a randomly selected number and arrow, at a specified height at the end of the experiment area. After the ambient illumination value was stabilized, the participant walked to the sign in a straight line of the specified angle from the starting point of the experiment area. The participants were asked to observe the message on the signs as they moved at the speed they normally traveled in the metro stations. The moment the participant could see the numbers and arrows on the sign and read them out accurately, he/she stopped and the experimenter measured the distance between the participant and the sign and recorded it. Then, the participant returned to the starting point and turned their back to the experiment device. The experimenter changed the parameters, such as the sign, the height, or the angle, to the next combination. The experiments were repeated until the participants completed the first group of 12 scenarios. The experimenter turned half of the lights off, to keep the ambient illumination around 70 lux. When the illumination was stable, the experimenter and participants repeated the experiment for the next 12 scenarios.

### 2.7. Data Analysis

The legibility distance was recorded in the experiment, which is the maximum distance from which a participant can read or identify the contents of the sign. The farther the legibility distance, the better the readability of the sign. The Statistical Package for Social Science (SPSS) was used to conduct analyses of variance (ANOVA) and the Matrix Laboratory (MATLAB) was used to visualize data and fit the visibility catchment area (VCA).

## 3. Results

The mean values of legibility distances for each independent variable are listed in Table 3. As presented in Section 2.2, the experiment had four independent variables: ambient illumination (two levels), color combination (two levels), sign height (two levels), and observation angle (three levels). Thus, the total number of trials was obtained by multiplying all levels of independent variables with the total number of 20 participants, that is,  $20 \times 2 \times 2 \times 2 \times 3 = 480$ .

**Table 3.** Mean and standard deviation (SD) of legibility distance for each level of the independent variables (participants  $n = 20$ ).

| Independent Variables | Number of Trials | Mean (m) | SD    |
|-----------------------|------------------|----------|-------|
| Ambient contrast:     | 480              | 37.74    | 17.76 |
| 70 lux                | 240              | 35.26    | 17.85 |
| 273 lux               | 240              | 40.21    | 17.37 |
| Color combination:    | 480              | 37.74    | 17.76 |
| Chromatic             | 240              | 36.78    | 17.71 |
| Achromatic            | 240              | 38.70    | 17.80 |
| Sign height:          | 480              | 37.74    | 17.76 |
| 1.5 m                 | 240              | 38.17    | 17.81 |
| 2 m                   | 240              | 37.30    | 17.75 |
| Observation angle:    | 480              | 37.74    | 17.76 |
| 0°                    | 160              | 48.51    | 15.18 |
| 45°                   | 160              | 40.63    | 15.46 |
| 70°                   | 160              | 24.08    | 12.98 |

### 3.1. ANOVA Analysis

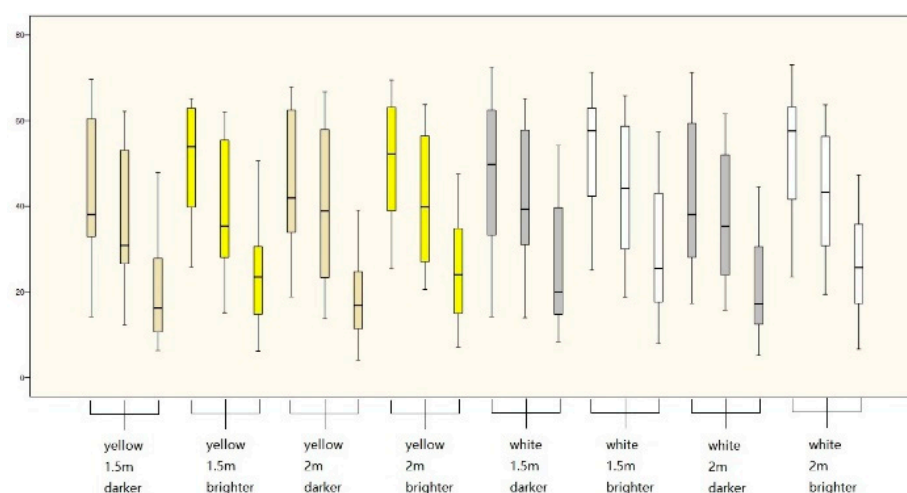
The results with respect to ambient illumination, color combination, sign height, and observation angle, along with ANOVA summaries, are shown in Table 4 and Figure 5.

The main effect of ambient illumination ( $F_{1,211} = 13.910$ ,  $p < 0.01$ ) reached statistical significance. Whether chromatic or achromatic, the legibility distance of high ambient illumination was always longer than that of low ambient illumination, as shown in Figure 6. Achromatic (average legibility

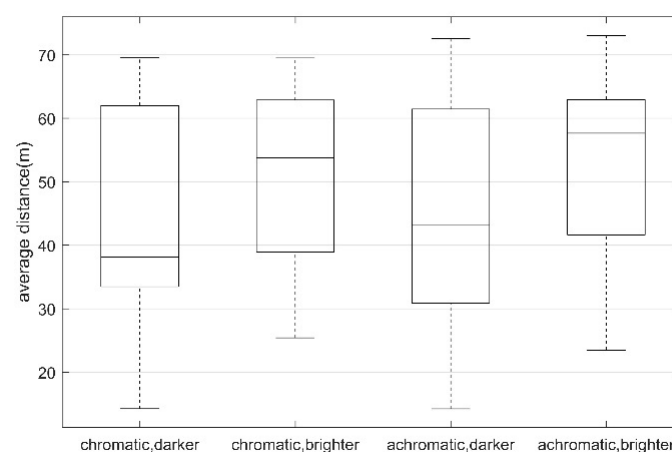
distance = 53.30 m) was more legible than chromatic (average legibility distance = 50.84 m) in bright ambient illumination. Whether the height of the sign was 1.5 m or 2 m, the legibility distance of high ambient illumination was always longer than that of low ambient illumination, as shown in Figure 7. The sign height of 1.5 m (average legibility distance = 45.60 m) was more legible than that of 2 m (average legibility distance = 44.28 m) in dark ambient illumination. The legibility distance of high ambient illumination was always longer than that of low ambient illumination in these three angles, as shown in Figure 8.

**Table 4.** Analysis of variance (ANOVA) of legibility distance.

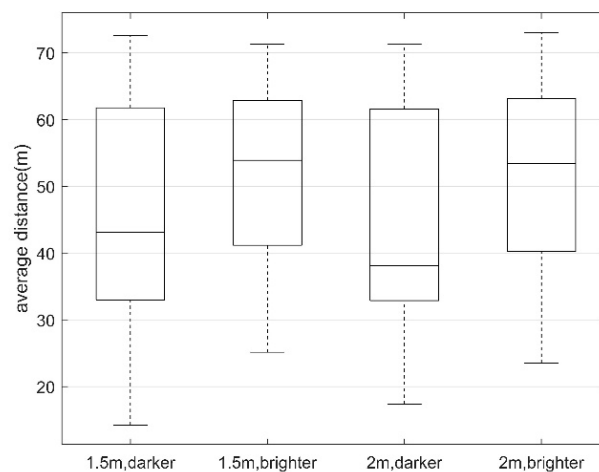
| Sources                  | Df  | Mean Square | F       | Partial Eta Squared |
|--------------------------|-----|-------------|---------|---------------------|
| Ambient illumination (I) | 1   | 2943.761    | 13.910  | 0.000               |
| Color combination (C)    | 1   | 441.345     | 2.085   | 0.149               |
| Sign height (H)          | 1   | 90.443      | 0.427   | 0.514               |
| Sign angle (A)           | 2   | 24870.400   | 117.515 | 0.000               |
| C*H                      | 1   | 493.504     | 2.332   | 0.127               |
| C*I                      | 1   | 84.024      | 0.397   | 0.529               |
| C*A                      | 2   | 49.543      | 0.234   | 0.791               |
| H*I                      | 1   | 49.249      | 0.233   | 0.630               |
| H*A                      | 2   | 52.210      | 0.247   | 0.781               |
| I*A                      | 2   | 155.470     | 0.735   | 0.480               |
| Error                    | 456 | 211.637     |         |                     |



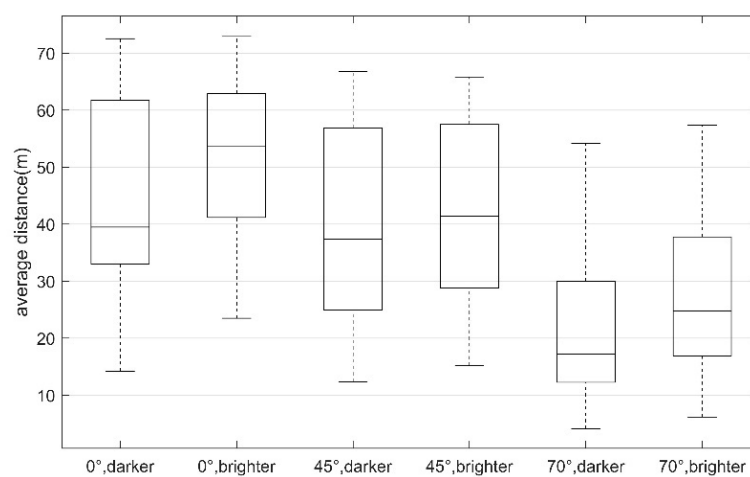
**Figure 5.** Legibility distance box-plot (x\_axis: scenarios; y\_axis: legibility distance (m)).



**Figure 6.** Legibility distance of ambient illumination and color combination.



**Figure 7.** Legibility distance of ambient illumination and sign height.



**Figure 8.** Legibility distance of ambient illumination and observation angle.

The main effect of observation angle ( $F_{2,211} = 117.515$ ,  $p < 0.01$ ) also reached statistical significance. The Tukey test (Table 5), at  $\alpha = 0.05$ , showed that legibility distance at  $0^\circ$  (from the centerline) (48.51 m) was significantly better than that at  $45^\circ$  (40.63 m). Moreover, legibility distance at  $45^\circ$  (40.63 m) was significantly better than that at  $70^\circ$  (24.08 m). At each angle, achromatic signs were more legible than chromatic signs. For achromatic signs, the legibility distance was 49.11 m (seen at  $0^\circ$ ), 41.2 m (seen at  $45^\circ$ ), and 25.68 m (seen at  $70^\circ$ ). Meanwhile, for chromatic signs, the legibility distance was 48.51 m (seen at  $0^\circ$ ), 40.53 m (seen at  $45^\circ$ ), and 24.08 m (seen at  $70^\circ$ ). As the angle increased, the gap increased. At each angle, the height of the sign showed different, but insignificant effects (Figure 9).

**Table 5.** Tukey grouping of legibility under different observation angles.

| Observation Angle Legibility       | 0° 48.51 | 45° 40.63 | 70° 24.08 |
|------------------------------------|----------|-----------|-----------|
|                                    | A        |           |           |
| Tukey grouping ( $\alpha = 0.05$ ) | B        |           | C         |

Note: In the same letter group, means are not significantly different.

The main effect of color combination ( $F_{1,211} = 2.085$ ,  $p > 0.01$ ) did not reach statistical significance. Under the 1.5 m height scenario (Figure 10a), achromatic signs were more legible than chromatic signs, whether the ambient illumination was dark or bright. The achromatic signs in the dark environment

were even more legible than the chromatic signs in the bright environment at 45° and 70°, but under the 2 m height scenario (Figure 10b), there was no such trend shown.

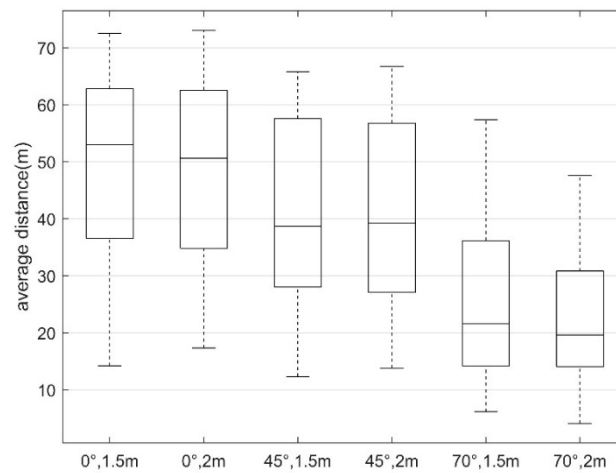


Figure 9. Legibility distance of observation angle and sign height.

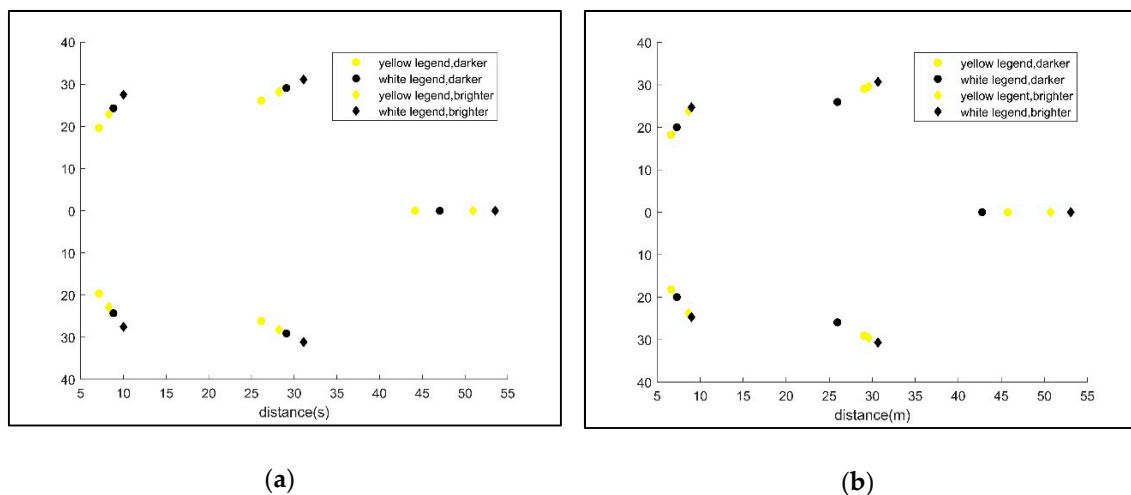


Figure 10. Color combination comparison: (a) sign height = 1.5 m; (b) sign height = 2 m.

The main effect of sign height ( $F_{1,211} = 0.427$ ,  $p > 0.01$ ) did not reach statistical significance. None of the four independent factors had significant interaction effects.

### 3.2. The Fitting Results

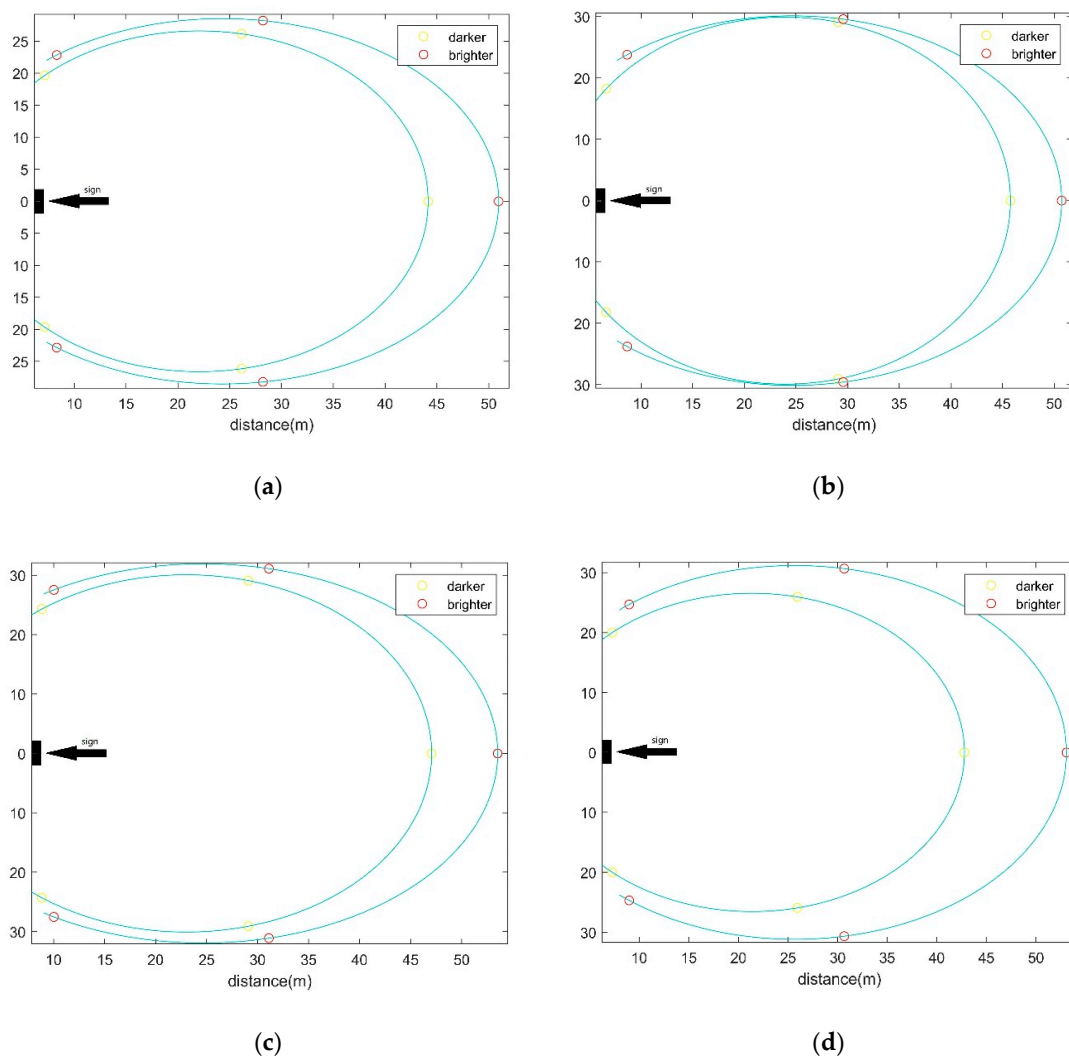
Figure 10 shows that the shape of the connecting line, based on the average legibility distance measured from different angles, is like an ellipse. The mean distance was fitted to get different elliptic curves (in the situation at 0°) in each situation. The center point of the ellipse, the long axis, and the short axis is shown in Table 6. Taking Figure 11a as an example, the fitting formulas for its curves are as follows:

$$a : \text{Darker} : \frac{(x - 22.0531)^2}{53.2068^2} + \frac{y^2}{44.2078^2} = 1 \quad (1)$$

$$b : \text{Brighter} : \frac{(x - 24.2840)^2}{57.0383^2} + \frac{y^2}{53.3340^2} = 1 \quad (2)$$

Table 6. Results of fitting curves.

| Scenario   |       |        | Center Point (x) | Center Point (y) | Long Axis | Short Axis | Mean Distance |
|------------|-------|--------|------------------|------------------|-----------|------------|---------------|
| Chromatic  | 1.5 m | dark   | 22.05            | 0                | 53.21     | 44.21      | 44.18         |
|            |       | bright | 24.29            | 0                | 57.04     | 53.33      | 50.95         |
|            | 2 m   | dark   | 23.94            | 0                | 59.83     | 43.65      | 45.77         |
|            |       | bright | 24.66            | 0                | 60.24     | 52.14      | 50.73         |
| Achromatic | 1.5 m | dark   | 23.01            | 0                | 60.13     | 48.09      | 47.05         |
|            |       | bright | 24.64            | 0                | 63.82     | 57.79      | 53.53         |
|            | 2 m   | dark   | 21.37            | 0                | 53.12     | 42.82      | 42.78         |
|            |       | bright | 25.7033          | 0                | 62.38     | 54.74      | 53.07         |



**Figure 11.** Legibility distance fitting curves: (a) chromatic and 1.5 m; (b) chromatic and 2 m; (c) achromatic and 1.5 m; and (d) achromatic and 2 m.

In Figure 12, the value of the short axis was linearly related to the corresponding average legibility distance, with the value of  $R^2$  reaching 0.949, demonstrating a high correlation. When selecting and evaluating the location of the signage layout, the ellipse visibility catchment area can be used for calculation. Moreover, the setting location of the signage should be avoided if it is set away from the passengers' centerline or if it will be blocked by pillars. However, there was no high linear relationship between the long axis and the legibility distance.



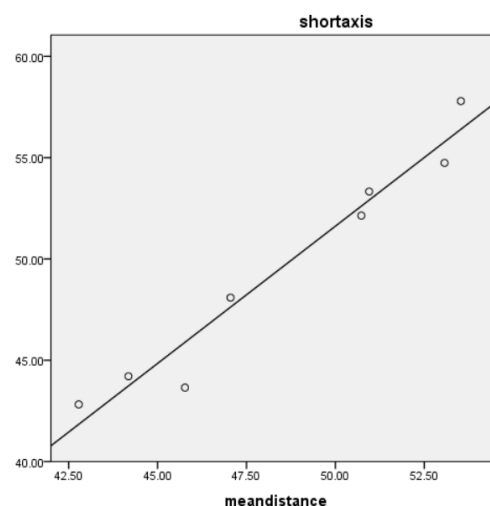


Figure 12. The relationship between the mean distance and short axis of fitting curves.

## 4. Discussion

### 4.1. Ambient Illumination

The study found that the legibility distance increased by 14% under high ambient illuminance (273 lux) compared with under low ambient illuminance (70 lux) in terms of the metro station signs. Under negative image polarity, whether the sign was chromatic or achromatic, or whether the sign height was 1.5 m or 2 m, a higher ambient illumination resulted in longer legibility distance. These results are consistent with the previous findings of Knez and Kers [22], who indicated that indoor lighting directly affects users' emotions, memory, perceptual-orientation, and problem-solving abilities. Moreover, Hidayetoglu et al. [24] observed that, parallel to the increase in the level of brightness, the perceptual evaluations of the participants increased in a positive direction. As our designed sign was not backlit, the findings also supported the study of Lasauskaite and Reisinger [34], who showed that when the wayfinding sign was off, conspicuity was higher in the high ambient light condition (130 lux) than in the low ambient light condition (40 lux). These results are also in line with the study of Dobres et al. [23], who presented that display time needed to identify a word was reduced globally under conditions of high ambient illumination. The findings of Liu [25] showed that, for phosphorus signage, the mean visual distance with illumination is greater than that without illumination.

### 4.2. Color Combination

This study showed that the legibility of achromatic signs (white text on black background) and achromatic signs (yellow text on black background) had different, but insignificant effects. The legibility distance of the achromatic signs is increased by 5% compared with that of the chromatic signs, which is consistent with the finding of Nilsson [34], who found that, at the text size of 36 pt, the mean legibility distance of a white-on-black sign is 492 cm, and that of the yellow-on-black sign is 484 cm, which means achromatic is better for sign legibility. However, color combination did not have significant effects on legibility, which can be explained by the study of Buchner and Baumgartner [35], who claimed that when display illumination is held constant across polarity conditions, the positive polarity advantage is eliminated, and only the overall illumination of the display itself affects reading accuracy.

The formula for calculating the color contrast ratio is as follows: Contrast ratio:

$$\text{Contrast ratio : } C = \frac{L1 + 0.05}{L2 + 0.05} \quad (3)$$

where  $L_1$  is the relative luminance of the lighter of the colors and  $L_2$  is the relative luminance of the darker of the colors. For the sRGB color space, the relative luminance of a color is defined as follows:

$$\text{Relative luminance : } C = 0.2126 \times R + 0.7152 \times G + 0.0722 \times B \quad (4)$$

where  $R$ ,  $G$ , and  $B$  are defined as follows:

$$\begin{aligned} \text{If } R_{sRGB} \leq 0.03928, \text{ then } R &= R_{sRGB}/12.92; \text{ else } R = ((R_{sRGB}+0.055)/1.055)^{2.4} \\ \text{If } G_{sRGB} \leq 0.03928, \text{ then } G &= G_{sRGB}/12.92; \text{ else } G = ((G_{sRGB}+0.055)/1.055)^{2.4} \\ \text{If } B_{sRGB} \leq 0.03928, \text{ then } B &= B_{sRGB}/12.92; \text{ else } B = ((B_{sRGB}+0.055)/1.055)^{2.4} \end{aligned} \quad (5)$$

Moreover,  $R_{sRGB}$ ,  $G_{sRGB}$ , and  $B_{sRGB}$  are defined as follows:

$$R_{sRGB} = R_{8bit}/255, G_{sRGB} = G_{8bit}/255, B_{sRGB} = B_{8bit}/255 \quad (6)$$

The results of the calculation of the color contrast ratio are shown in Table 7. The contrast ratio of white text on black background is 43.28% better than yellow text on black background, which is consistent with our finding that legibility distance of the white-on-black signs is increased by 5% compared with that of the yellow-on-black signs. Therefore, the combination of different text and background colors has a certain influence on the visual identity of the signs. The higher the color contrast ratio, the longer the legibility distance.

**Table 7.** The result of contrast ratio.

| Background Color | Text Color | Contrast Ratio |
|------------------|------------|----------------|
| Black            | White      | 21.00          |
| Black            | Yellow     | 14.97          |

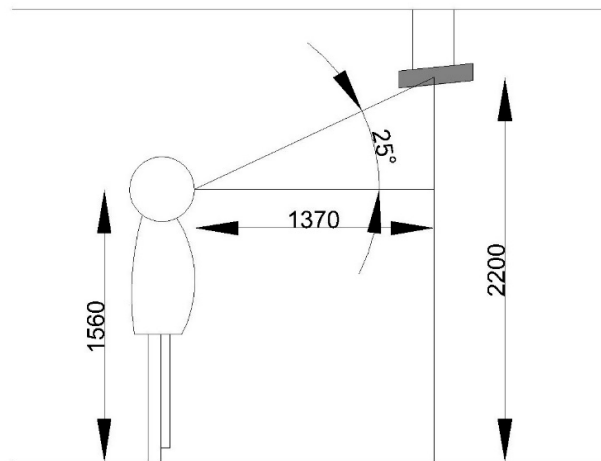
On the other hand, this study is inconsistent with findings of Ko [36], who found that the legibility index of the yellow-on-black sign was 0.818, while that of white-on-black was 0.789. Luria et al. [37] observed that yellow target letters on dark backgrounds produced the fewest errors. Lin [30] also showed a somewhat greater grand-mean visual preference for chromatic text (67.41%) than for achromatic text (62.36%).

There are three explanations for the result. First, the type of dependent measure of sign/screen is different. The dependent variable in this experiment was the legibility distance, which is the farthest position that participants could read the contents of a particular sign with 100% accuracy. The dependent variable for some other experiments was reading accuracy [30,36,37]. Second, the effect of text color may be obscured when screen luminance combination is adequate [38,39]. The materials used in our experiment were noctilucent materials. The luminance of the plate surface was sufficient in both dark and bright environments. Therefore, in terms of legibility, the visual differences caused by the color effect may be little during the experimental trials. Third, the background color of the sign board used in the experiment was all black, which may reduce the color contrast. Huang [29] suggested that achromatic color was the most effective background chromaticity with lower reading time and had a higher preference rating. Considering that, in this experiment, the background color is achromatic and belongs to the optimal class, the difference may be small.

#### 4.3. Sign Height

This study presented that the main effect of sign height did not reach statistical significance. When the line of sight is horizontal, the visual range of the vertical field of view is approximately 25 degrees up and 30 degrees down [33]. The horizontal sightline of passengers is 1.56 m ( $\approx 3.28$  ft), according to the “China Bureau of Technical Supervision”. When the distance between passengers and the sign was greater than 1.37 m, the sign installation height would not affect the perception of the sign by

passengers, as shown in Figure 13. When the distance was less than 1.37 m, passengers could usually identify the sign by raising or lowering their head. Therefore, the installation height of the sign has less of an effect on the visibility catchment area.

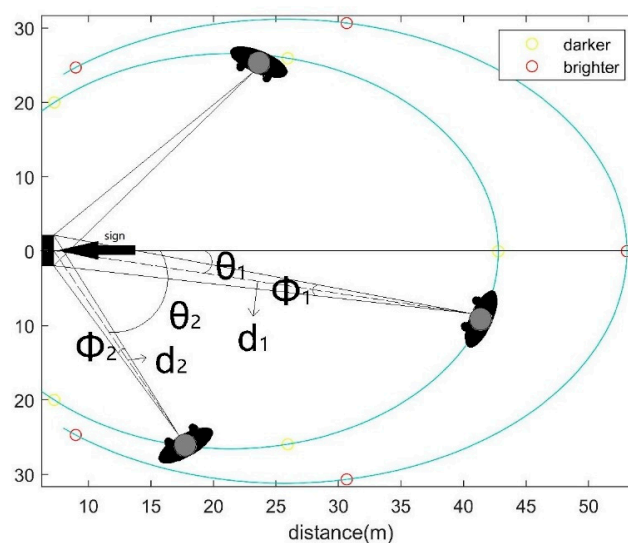


**Figure 13.** The relationship between visual field and sign height (unit: mm).

The findings of Lin [38] showed that, when the pedestrian rate is 1500 p/h, the height of guiding signs does not have a substantial influence on pedestrians. Therefore, considering that there was no interference from other pedestrians in our experiment and the rate is much less than 1500 p/h, the sign height had little effect on passengers.

#### 4.4. Observation Angle and Visibility Catchment Area (VCA)

This study found that the observation angle had a significant effect on the legibility distance. The legibility distance at 0 degrees (from the center line) was 19% longer than that at 45 degrees. The legibility distance at 45 degrees was 69% longer than that at 70 degrees. It can be explained that, for a sign of given size, as the observation angle ( $\theta$ ) increases, the maximum viewing distance ( $d$ ) must decrease, in order to resolve the angular separation ( $\phi$ ) of the sign [31], as shown in Figure 14. As the viewing angle increases, the visual stimuli become distorted [40] and anisotropy increases [17], resulting in degraded legibility.



**Figure 14.** The relationship between observation angle, angular separation, and legibility distance.

The corresponding fitting curves for VCA were like an ellipse at a high level. The short axis value was linearly related to the corresponding average legibility distance ( $R^2 = 0.949$ ), which is inconsistent with previous findings [25]. However, Xie et al. [31] theoretically found that VCA had a circular appearance, with diameter approximately equivalent to the radius of the assumed legibility distance at 0 degrees. Through the experiment they did afterwards, however, the curve was more like an ellipse rather than a circle, as depicted in Figure 15, which is in favor of this study.

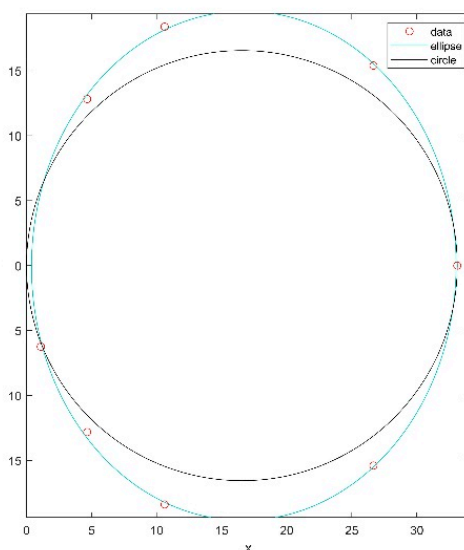


Figure 15. The fitting curve of the previous study.

## 5. Conclusions

According to the current situation of the metro stations in Shanghai, the effects of two color combinations of inbound and outbound streamlines, two signage setting heights of wallpaper and suspended signs, three passengers' observation angles, and two values of ambient illumination on the wayfinding signs' legibility were studied through experiments.

On the basis of this study, particular ambient illumination, color combination, sign height, observation angle, as well as visibility catchment area are recommended to potentially aid in designing sign layout and choosing setting locations in Shanghai metro stations. We suggest that the metro stations should not use low ambient illumination, which will significantly decrease signs' legibility distance. The signs for inbound and outbound streamline in Shanghai metro stations had similar legibility distance. The setting height of wallpaper signs (1.5 m) and suspended signs (2 m) did not significantly affect legibility. Considering that wallpaper signs are nearly horizontal to people's sightline, which may be blocked by the passenger flow, although the legibility distance of wallpaper signs is longer, the metro stations should choose more suspended signs to ensure an unblocked visibility catchment area. The VCA was more like an ellipse rather than a circle, with the short axis nearly equal to legibility distance when the observation angle is 0 degrees. To ensure reliable recognition and comprehension of signage information, safety signs are required to conform to certain design criteria specified in various national and international standards and guideline documents [31]. Therefore, our research can provide the experimental basis for the establishment of the standards of internal signage systems in metro stations in Shanghai.

According to the experimental results, the study of the legibility distance of the signs in different environments and different streamlines can provide the basis for the selection of the quantities and locations of the signs in the metro station. For example, in the long corridors, in order to eliminate the restlessness and anxiety of passengers in the process of walking, and to prevent passengers from turning back to the entrance of the corridors to confirm the message, the location of signs in the station

needs to meet the requirements of continuity. However, too many signs will increase the economic cost and the cost of electrical resources. According to the legibility distance, reasonable setting locations can meet the requirements of economic and environmental sustainability, achieving the optimization between minimizing the economic cost and maximizing the guiding efficiency. Owing to lack of natural visibility and orientation, it is important to consider underground space connectivity not only in terms of physical connectivity, but also in terms of visual and implicitly connectivity [41]. When the passengers are within the legibility distance of the sign, they can perceive the functional attributes of the next space through the directional message, even if the sightline is not directly connected. Our work about the legibility distance of wayfinding signs in metro stations can provide a data basis for the application of space syntax methodology in the metro station. The passengers are influenced by the wayfinding system in the process of seeking the way, and show the behaviors of moving forward, stopping, accelerating, decelerating, and so on [3]. Our research on the visibility catchment area of signs can provide the basis for the further revision of the micro-simulation model of pedestrians in the metro station. Meanwhile, calculating the effective area repetition rate of the signage system owing to the VCA defined in our work can provide the basis for the evaluation system model of the metro station.

Although this study was carefully prepared, some limitations were unavoidable. First, in real metro stations, there exist self-illuminated advertisement billboards. This experiment did not take the influence of billboards on the conspicuity and visibility of signs into account. In the future, the experimental environment should be more similar to the real metro station environment and the legibility of brand icons on such backgrounds could be a worthwhile research project. Second, in this paper, the sign layout elements were limited to numbers and arrows, which are the two most used identifiers in the specific metro station environment. However, real signs also contain Chinese and English text and icons, which can cause the legibility distance to change. In the future, the relationship between numbers and text in terms of legibility distance needs to be explored. Third, the walking and crowding behavior of passengers in metro stations will affect the participants' seeking behavior and eyesight line, which may affect signs' legibility and visibility. Fourth, how the signage affects traffic behavior is a subject that needs further study. For example, whether the pedestrian's walking speed changes because they are looking at the sign, and whether there are behaviors such as avoiding, following, surpassing, and lateral moving.

**Author Contributions:** Conceptualization, Y.S. and C.L.; methodology, Y.S., C.L., and Y.Z.; software, Y.S.; validation, Y.Z.; formal analysis, Y.S. and T.W.; investigation, Y.S. and T.W.; resources, Y.S.; writing—original draft preparation, Y.S.; writing—review and editing, Y.Z.; visualization, Y.S.; supervision, Y.Z.; funding acquisition, C.L. and S.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Social Science Foundation of China (Project 18BSH143), Shanghai Science and Technology Innovation Action Plan (19DZ1208800), and the Scientific Research Project of Shanghai Municipal Science and Technology Commission (17DZ1204000).

**Acknowledgments:** We truly appreciate the opportunity to explore the topic by fund.

**Conflicts of Interest:** The authors declare no conflict of interest.

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