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# Designing Perennial Landscapes: Plant Form and Species Richness Influence the Gaze Perception Associated with Aesthetic Preference

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**Citation:** Shi, Y.; Zhang, J.; Shen, X.; Chen, L.; Xu, Y.; Fu, R.; Su, Y.; Xia, Y. Designing Perennial Landscapes: Plant Form and Species Richness Influence the Gaze Perception Associated with Aesthetic Preference. *Land* **2022**, *11*, 1860. https://doi.org/10.3390/land11101860

Academic Editor: Diane Pearson

Received: 21 September 2022
Accepted: 19 October 2022
Published: 20 October 2022



**Abstract:** The up-close experience of perennial landscapes has been shown to enhance residents' perception of naturalness in the context of increasing small-scale vegetation landscapes. This study explored how formal aesthetic characteristics were related to landscape perception and whether landscape preference correlated with eye movements. We created a series of photomontages showing perennial combinations that contained different plant forms, degrees of species richness, and plant arrangements and recorded 73 participants' eye movements during 10 s of free viewing in Experiment A and task-oriented viewing in Experiment B and ratings of landscape preference collected through rating scales. We found that the effects of plant form and species richness were significant for gaze behavior, while arrangement showed no significant effect. We also found that landscape preference was positively correlated with fixation count but negatively correlated with mean fixation duration and total fixation duration. Additionally, women had more but shorter fixations than men while viewing these photomontages, and the difference in aesthetic preferences between men and women was not significant. Concerning the different professional background groups, no significant gaze behavior difference between professionals and nonprofessionals was detected, but compared with professionals, nonprofessionals tended to give strongly higher preference ratings. The outcomes shed light on the influence of formal aesthetic characteristics on gaze behavior and advanced the application of eye-tracking technology in perennial landscape studies. Our findings also confirmed the efficiency of vegetation landscapes designed based on public preferences for providing restoration from stress or fatigue.

**Keywords:** perennial; formal aesthetic; landscape perception; preference; eye-tracking; visual attention

## 1. Introduction

The urban green space is an indispensably major part of the city. Diverse vegetation provides city residents with psychological perception change in addition to aesthetic experiences, such as positive emotion inducement, stress reduction, and cognitive-behavioral rehabilitation, etc. [1–3]. As cities plan for post-COVID recovery, green infrastructure expansion is gaining increasing attention as a particular strategy of improving citizens' wellbeing and urban ecosystems [4–6].

Plants fulfill important functions in urban green space, "without plants everything is grey and ugly" [7]. Recent urban vegetation landscape research has focused mainly on large-scale landscapes, such as forests [8], urban parks [9], and greenways [10], although the types of public urban green space also include roadside greenery, spaces around public facilities and relatively small areas embedded between buildings [7]. In rapidly expanding cities, community segregation and landscape fragmentation result in small-scale vegetation landscapes increasing [11]. More current vegetation landscape research considered flower borders [12], small vegetation patches [5], and herbaceous plant communities [13]. As a type of small-scale and low-maintenance vegetation landscape, perennial landscapes take advantage of plant adaptation and mitigation capacities to promote species diversity and improve ecological benefit [14–16]. Meanwhile, an enriched perception of naturalness may be enhanced by up-close experience of the perennial landscapes, which also has benefits for citizens' health and wellbeing [17]. According to Roger Barker's Behavior Setting Theory [18], the physical environment is a key factor influencing sensory experience and affective responses. For example, viewing urban scenes generated significantly more fixations than viewing nature scenes, while viewing nature scenes resulted in significantly higher positive affect [19]. Nevertheless, in terms of both influence of landscape characteristics on viewing behavior and preference by the public, very few studies have systematically and quantitatively analyzed perennial landscapes.

Formal aesthetics usually focuses on the landscape's visual structural and geometric properties, including shapes, rhythms, complexities, and sequences [20]. For formal aesthetic properties of woody plants, plants were regarded as an expression of form and texture [21]. Based on Gestalt theory, different silhouette shapes were extracted from planting design, and then were organized in the landscape through order, rhythm, repetition, and harmony [21]. Additionally, the shape, size, color, and texture of the plants influence the landscape perception and interpretation [22]. Although these studies were about trees or shrubs, in the perennial combinations, the forms of plants are also important considerations. Plant form in this study means the overall outline of plants seen from a distance. The classification of selected species in terms of plant forms does not apply to all plants. DiSabato-Aust [23] considered plant forms to be mounding, vertical, conical, weeping, creeping, or irregular. Therefore, plant forms, described as one formal aesthetic feature, can be simplified and extracted based on the gestalt proximity and similarity principle, which allows viewers to interpret landscape structure easily. Furthermore, numerous studies have indicated that the aesthetic appreciation of planting landscapes increases with an increase in species richness, which plays a key role in the landscape complexity of visual perception [9,24,25]. Changes in vegetation structure also importantly contribute to the perception of naturalness in landscapes [26]. Individuals could perceive natural environment by virtue of different arrangements of plants, for instance, repetition or gradual changes of plants provide rhythm that generally generates higher aesthetic value [21]. Aesthetically desirable perennial landscapes bring calmness and peace via its changing plants [27]. Thus, plants of different forms can be combined to build an ideal landscape with different degrees of species richness according to aesthetic principles.

A series of methods and models for landscape preference have been developed in the last two decades [28–30]. Landscape aesthetic values are determined by the characteristics of the landscape and human perception or judgment [31]. However, the reliability and validity of descriptive inventories and public preference models that rely on expert evaluations or questionnaires are usually influenced by uncertainties, such as sample error and underlying subjectivity [28]. A combination of subjective and objective methods has been recently used in research on landscape preference in many studies [12,24,32,33]. Eye movements are used to extract information from environment and need not invoke behavioral responses with a complex decision; consequently, subjective anticipated effects can be eliminated to obtain more objective results [34]. Previous research observed a strong correlation between aesthetic preference and eye movements [35]. Cottet et al. [32] conducted a series of eye-tracking trials in which the authors compared the information provided by rating, verbal, and gaze data. The authors concluded that gaze data help identify important landscape objects influencing how landscapes are perceived and evaluated. More recently, literature that offered contradictory findings on the relationship between landscape preference ratings and gaze behavior has emerged. Batool et al. [36] discovered that there was a positive correlation between preference ratings and fixation count when viewing photographs of urban views; this finding is consistent with the findings of Huang and Lin [24] who used landscape photographs. In contrast to these findings, however, Liu et al. [37] found no definite relationships between preference ratings and fixation counts in various urban green space settings. It would therefore be of interest to know whether and how preference ratings of perennial landscapes correlated with eye movements in the case of task-oriented viewing. The answers to this question may help to better understanding the visual reward mechanisms, which are tuned based on information in the environment related to survival and well-being to motivate the pursuit of adaptive behavior [19].

Herein, different types of perennial combinations were used as stimuli, and we used traditional questionnaires and eye-tracking data to explore preference in the aesthetic experience and influence of formal aesthetic characteristics on visual behavior. As a basic eye-tracking metric, fixation, instead of all metrics, was selected to provide information about the main observation pattern examined in this study. Throughout the entire study, the eye-tracking metrics were therefore the following: fixation count, mean fixation duration, and total fixation duration. This paper seeks to investigate the differences in the visual perception of different perennial combinations based on formal aesthetic characteristics and clarify the correlation between preference ratings and gaze behavior of the test population. Specifically, this study aimed to address the following research questions: (1) which of the three formal aesthetic factors, namely, plant form, species richness, and arrangement, most influenced observation behavior; and (2) did the preference ratings of perennial landscapes correlate with eye-tracking data. The findings should importantly contribute to the field of perennial landscape design and offer some insights into the restorative and positive impact of vegetation landscape on city residents.

## 2. Materials and Methods

### *2.1. Materials*

In this case, 69 photographs, most of which represent the general perennials planting design, were taken in numerous gardens in Shanghai and Hangzhou. In this case, 29 common species and cultivars of herbaceous perennials (including parts of annual or biennial plants) (Table 1) and six plant arrangement patterns (Figure 1) were selected from these photographs. The perennial landscape photomontages used in this study were composed of the selected perennials and arrangements, which were based on the photographs of typically real outdoor environments. Then Photoshop was used to modify the above-mentioned photomontages, including the size, brightness and chroma. Consequently, these photomontages mitigated the variation compared to the unmodified photographs and would be familiar to participants.

**Table 1.** Classification of selected species in terms of plant forms.

| Mounding (M) | Conical (C) | Vertical (V) |
|---|---|---|
| *Brachyscome angustifolia* | *Hosta plantaginea* | *Ruellia simplex* |
| *Dianthus plumarius* | *Tarenaya hassleriana* | *Lavandula angustifolia* |
| *Gypsophila paniculata* | *Salvia nemorosa* 'Caradonna' | *Penstemon digitalis* |
| *Pelargonium hortorum* | *Pseudolysimachion spicatum* | *Achillea millefolium* |
| *Aquilegia viridiflora* | *Delphinium × cultorum* | *Rosmarinus officinalis* |
| *Pentas lanceolata* | *Salvia leucantha* | *Eupatorium cannabinum* |
| *Kochia scoparia* | *Liatris spicata* | *Verbena bonariensis* |
| *Ageratum conyzoides* | *Astilbe chinensis* | *Agastache rugosa* |
| *Agapanthus africanus* | *Salvia guaranitica* 'Black and Blue' | *Agapanthus africanus* 'Peter Pan' |
| *Gaura lindheimeri* | | |
| *Hibiscus grandiflorus* | | |

Note: The forms of selected plants were roughly divided into mounding, conical, and vertical based on Gestalt theory. Mounding includes plants with rounded spatial silhouettes; conical plant means plant size gradually decreased from bottom to top; vertical plants have upright stems and flowers (or inflorescences) of nearly identical height.

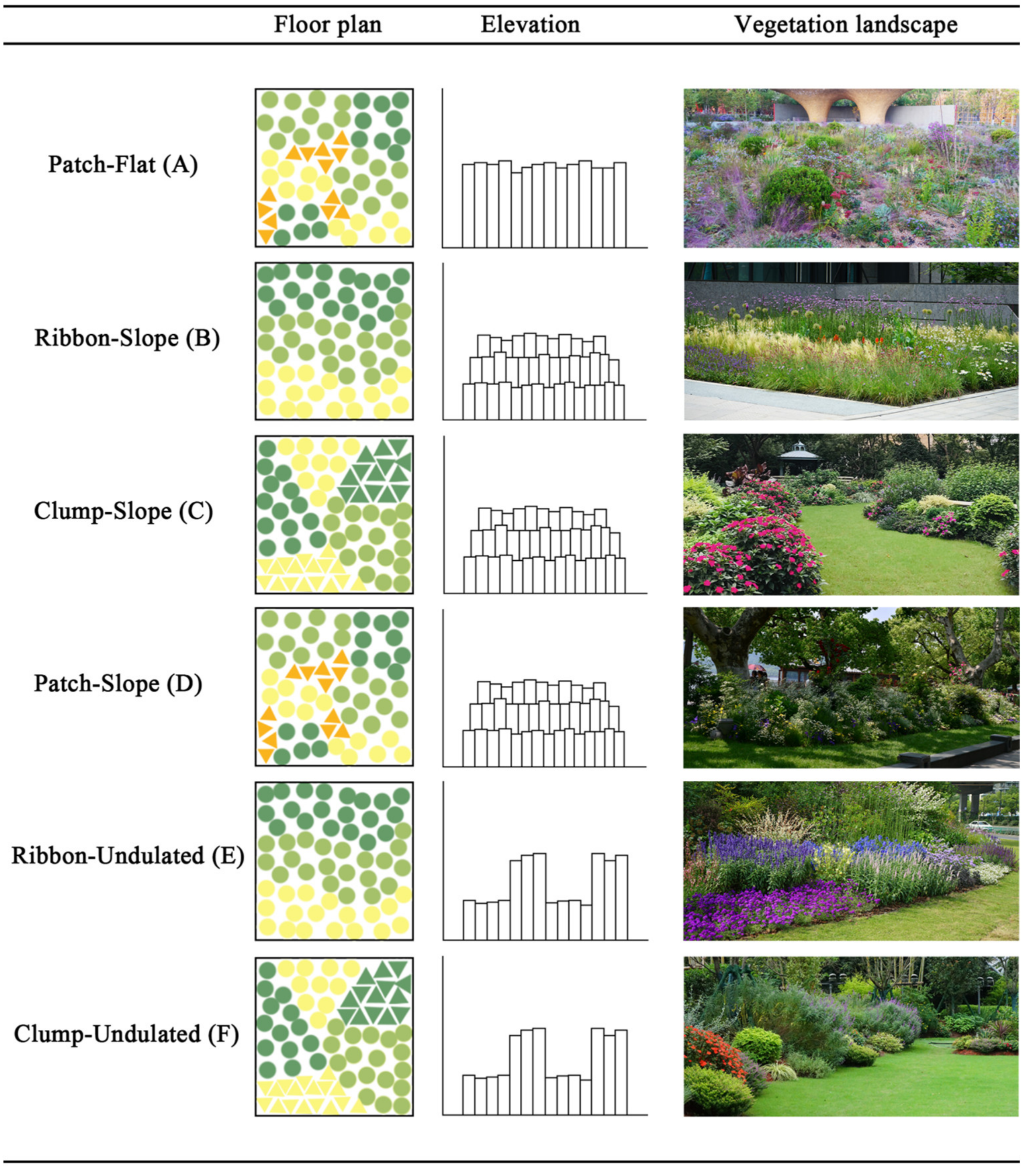


**Figure 1.** Spatial arrangement patterns for perennials planting landscape. Each legend in "Floor plan" and "Elevation" represents the layout of the plants, but not refer to a certain plant.

In Experiment A, to control the influence of irrelevant variables, vegetations of different forms, species richness, and arrangements were composed to create a series of landscape photomontages in an analogous color to investigate differences in the visual perception of different vegetation landscapes. Considering learning effects and visual fatigue, a Latin square design [29] rather than a common orthogonal array model was performed to reduce the number of photographs required for the experiment from 216 to 36. Figure 2 presents all photomontages of the vegetation landscapes tested. The top-down task was conducted to explore the impact of inner motivational disposition on viewing behavior and preference ratings in Experiment B. Specific photographs poorly represented the overall landscape quality [38]; thus, this experiment was repeated under conditions in which plant form was changed to improve reliability and validity. All 36 photomontages tested are presented in Figure 3. For the overall experiment, to guarantee an identical display, all 72 photomontages were framed in the same 1920 × 1080 pixel black background and calibrated to the same brightness and chroma with only the perennial combinations differing. The next section ("Procedure") describes the selection of background in more detail.

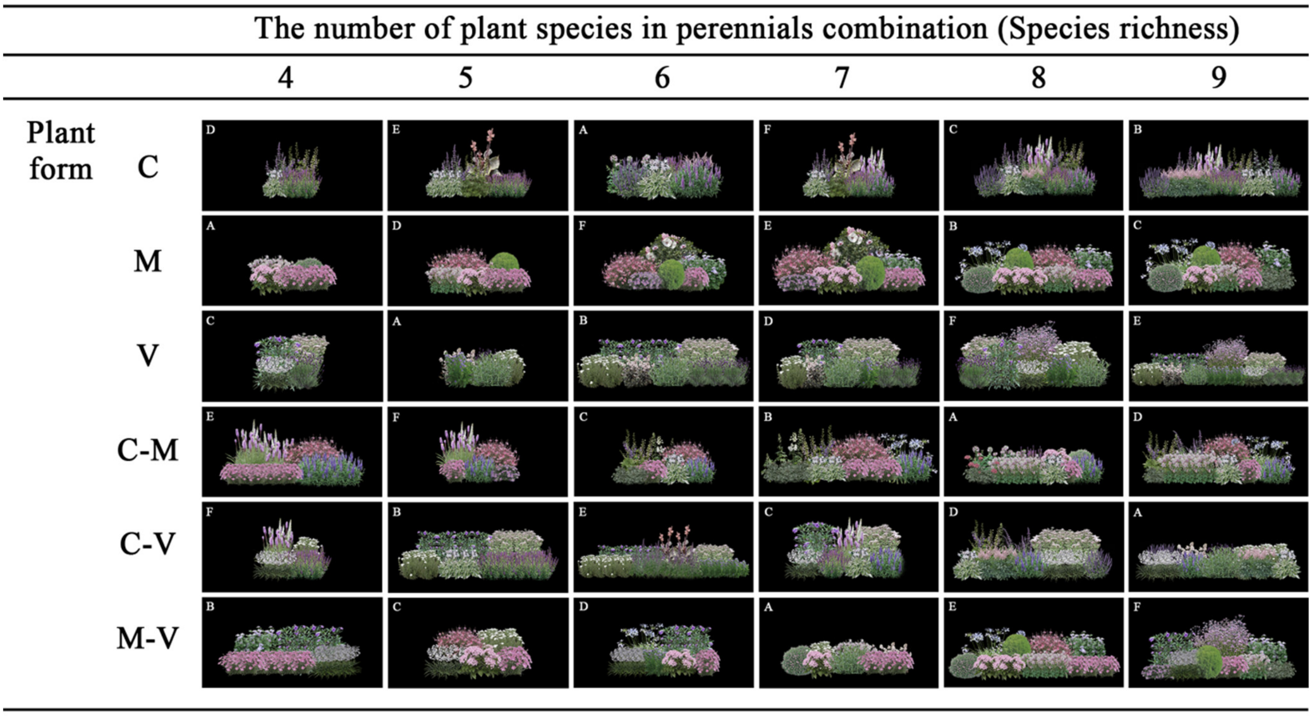


**Figure 2.** Visual stimuli (perennials landscape photomontages) utilized in experiment A. C, M and V represent conical, mounding and vertical, respectively. The letters in the upper left corner of each photomontage represent the plant arrangement patterns in Figure 1.

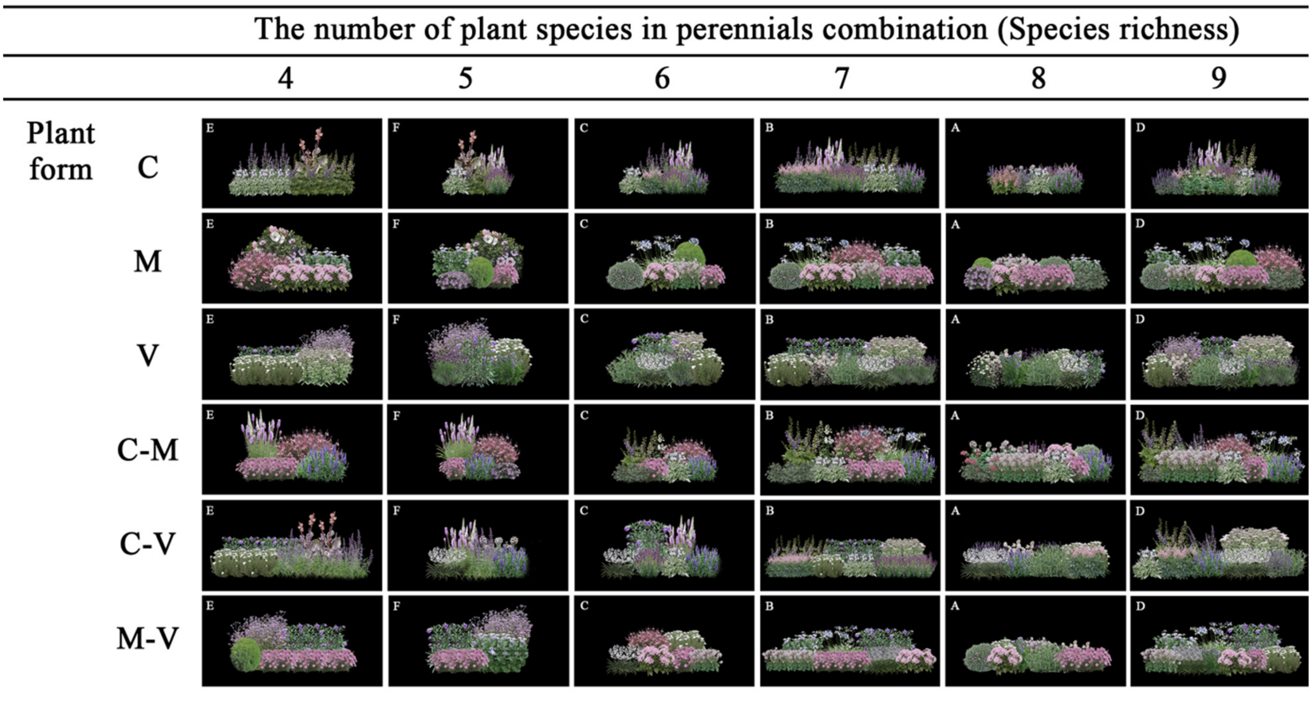


**Figure 3.** Presentation of the visual stimuli in experiment B. C, M and V represent conical, mounding and vertical, respectively. The letters in the upper left corner of each photomontage represent the plant arrangement patterns in Figure 1.

### 2.2. Experimental Protocol

#### 2.2.1. Participants

In total, 73 participants were recruited by posting information on the website for the eye-tracking experiment on landscape perception, and 43 participants simultaneously participated in landscape preference ratings. In experiment A, the 30 participants (14 males and 16 females, aged 19 to 54) included college students, teachers, and other school staff, constituting a representative sample of gender and age. The participants (22 males and 21 females, aged 20 to 30) in Experiment B were students and staff in different occupations and included 22 professionals associated with planting landscape design. The medium sample size in both experiments may not be large for studies of landscape perception but was sufficient for eye movement research to detect many major effects [37,39]. All participants had normal or corrected-to-normal visual acuity, and the degrees of myopia and astigmatism were required to be less than 400 and 200, respectively, to reduce eye-tracking measurement errors.

#### 2.2.2. Equipment

The eye-tracking experiments were performed using the Tobii TX300 Eye Tracker, which is equipped with a built-in user camera that enables for the recording of subjects' reactions to stimuli. The Tobii TX300 Eye Tracker is an unobtrusive eye tracker for detailed research of natural behavior and an integrated eye tracker that is supplied with a removable 23″ TFT monitor with a resolution of 1920 × 1080 pixels (Figure 4). The software used for the eye-tracking experiments was Tobii Studio, which offered a comprehensive platform for recording and analyzing eye gaze data. The experiments were carried out in an isolated room in the laboratory to prevent interference from infrared light, noise, and other factors.

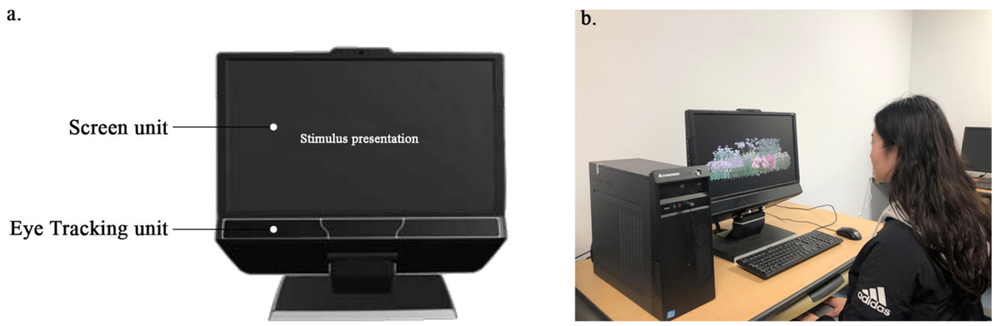


**Figure 4.** Eye-tracking equipment used for this study: (**a**) the Tobii TX300 Eye Tracker and (**b**) a participant experimenting.

#### 2.2.3. Procedure

Before commencing the study, ethical clearance was granted by the regional ethics committee, and written informed consent was obtained from all participants. After arriving at the lab, the participants completed a form requesting sociodemographic data. Next, the participants were informed of the experimental procedure and points for attention in the experiment. Next, a calibration procedure was conducted by having participants hold their gaze on five markers on the screen, and if the initial calibration was not inadequate, another calibration would be made. In Experiment A, since free viewing tasks were typically used to highlight the influences on eye movements stemming from the visual stimuli itself, the participants were given no particular tasks but were merely asked to freely view 36 randomly displayed photomontages, each for 10 s. In Experiment B, another group of participants was asked to perform a saccade task, in which they needed to direct their all gazes at the whole photomontage for 10 s; this internally motivated task was designed to eliminate potential interference between vegetation landscape differences and gaze behavior. After the demonstration of the still photomontages in Experiment B, a rating scale in which participants were asked to give these photomontages a preference rating from 1 to 10 was used to assess landscape preference. A scale of 1 to 10 indicates an increase in preference. While rating, to grasp the first impression, participants were instructed not to consider the photomontages for too long. The experiment lasted between 10 and 15 min for each participant.

The following concerns need to be considered in the procedure. First, a pilot study was performed before the main study to determine the photomontage backgrounds and fine-tune the experimental setup. The participants ($n = 4$) were seated 50–80 cm from the screen and asked to freely view some photomontages on a black background, white background and scenario simulation without time limits. When the participants thought they had viewed a photomontage fully, they notified the experimenter to end the timing. Their average viewing time was 8.7 s. The pilot study illustrated that the photomontage on a black background was more likely to focus participants' attention on the vegetation landscape. Thus, the specific display time was based on similar studies [40,41] and a pilot study, making each subject feel as comfortable as possible when viewing photomontage. Second, a dot in the center of a blank screen was shown for 3 s before the display of each photomontage to provide consistency on the initial conditions of the observation path.

### *2.3. Statistical Analysis*

#### 2.3.1. Analysis of Gaze Data

The initial eye-tracking data were gathered by Tobii Studio, and further statistical analyses were performed using SPSS 26.0 and Prism 8.0.

For the eye-tracking data pre-analysis in Experiment A, the Mahalanobis distance rather than a boxplot was conducted for multivariate anomaly detection (df = 3, $p < 0.001$) because of the joint distribution of fixation count, mean fixation duration, and total fixation duration, and then outliers caused by sensor errors and other abnormal events were removed. The Kolmogorov–Smirnov test results indicated that none of the eye-tracking data was normally distributed ($p < 0.05$) in all three eye-tracking data; thus, we could perform parametric tests only after converting the data to a normal distribution. The results of the exploratory analysis indicated that the fixation count and total fixation duration were negatively skewed (skewness < 0), and the skewness was more than three times the corresponding standard deviation. The new data showing a normal distribution would follow the following law:

$$Y_{converted} = 1/(MAX_{rec} + 1 - X_{rec}), \quad (1)$$

where

$Y_{converted}$ is the data of normal distribution after conversion
$MAX_{rec}$ is the maximum value of each group of recorded eye-tracking data
$X_{rec}$ is the original recorded eye-tracking data

The mean fixation duration was positive skewness (skewness > 0), and the skewness was more than three times the corresponding standard deviation; thus, the new data showing normal distribution would follow the following law:

$$Y_{converted} = 1/X_{rec}, \quad (2)$$

where

$Y_{converted}$ is the data of normal distribution after conversion
$X_{rec}$ is the original recorded eye-tracking data

The data analysis in Experiment A was based on the new data after the conversion. To investigate the impacts of formal aesthetic characteristics of perennial combinations on fixation behavior, we adopted the following approach. First, Levene's test was used to assess the prerequisite conditions of variance analysis. Roy's largest root multivariate test was conducted to analyze the significance of the main effects ($p < 0.05$). Tests of between-subject effects and post hoc tests were also performed.

In Experiment B, the Mahalanobis distance was used to remove outliers caused by sensor errors and other abnormal events. For Experiment B, the Kolmogorov–Smirnov test results indicated that none of the eye-tracking data was normally distributed ($p < 0.05$ in all three eye-tracking data); thus, the Mann–Whitney test (2 samples) for nonparametric data was used to test the equality of means based on ranks.

#### 2.3.2. Analysis of the Questionnaire Data

The ratings made for the 36 stimuli to which the subject had been exposed were statistically analyzed. Reliability analysis was carried out to evaluate the reliability of questionnaire data, and the results indicated that the questionnaire data were highly reliable ($\alpha > 0.9$). Kolmogorov–Smirnov test revealed that the questionnaire results followed a normal distribution ($p > 0.05$). Consequently, the data were analyzed for the parametric test (ANOVA) to assess the fascination of different planting landscape models (Tukey, $p < 0.05$). A scatter diagram and Spearman's product-moment correlation were used to determine the relationship between eye-tracking data and questionnaire data.

## 3. Results

### *3.1. The Impact of Formal Aesthetic Characteristics on Fixation Behavior*

Levene's test showed that the fixation count, mean fixation duration, and total fixation duration met the homogeneity of variance at $p > 0.05$. The results obtained from the tests of between-subjects effects revealed that apart from the studied effects (plant form, species richness, and arrangement), other effects that were not included in this study affected the participants' eye movements at $R^2 < 0.1$. The multivariate tests showed that only the plant form and species richness differed significantly at $p < 0.05$. Tests of between-subject effects indicated that the effects of plant form were significant for mean fixation duration, while species richness had a significant effect on fixation count and mean fixation duration (Table 2). These results also indicated that there was no statistically significant relationship between arrangement of plants and fixation metrics. The heat maps showed that participants had more fixations on unique flowers or tall plants stature in perennial combinations which have better rhythm in change of plant forms and arrangements (Figure 5).

**Table 2.** Effects of 'formal aesthetic' factors on landscape perception.

| | Fixation Count | Mean Fixation Duration | Total Fixation Duration |
|---|---|---|---|
| Plant form | 0.298 | 0.039 * | 0.082 |
| Specie richness | 0.005 * | 0.002 * | 0.121 |
| Arrangement | 0.489 | 0.281 | 0.586 |

Note: * Significant at $p < 0.05$.

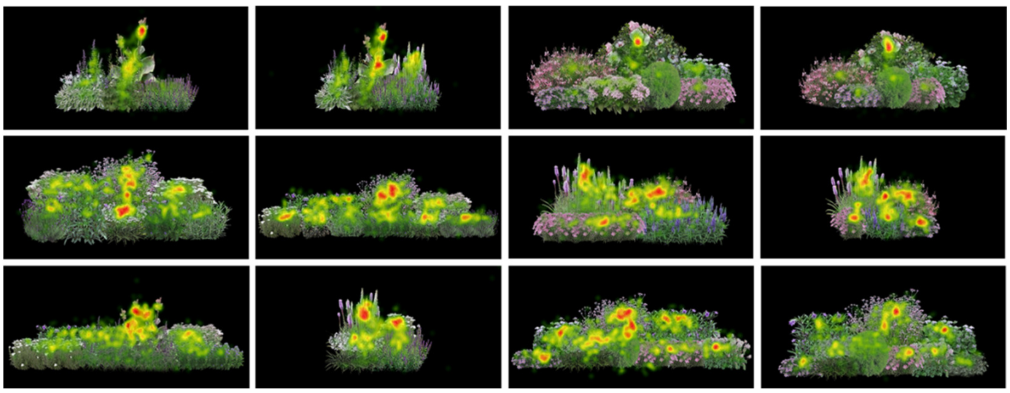

**Figure 5.** Eye-tracking heat maps of fixation duration of all participants on perennial combinations.

More specifically, Tukey comparisons based on the estimated means (Table 3) revealed that the fixation count was greater for the landscape composed of 9 species of plants than for both the landscapes of 4 and 5 species of plants. The fixation count differences of photomontage showing landscape compositions composed of 6, 7, and 8 species of plants were not significant. Overall, the fixation counts of landscape photomontages showing the different numbers of species were, in descending order, 9, 8, 6, 7, 5, and 4 species of plants. In addition, the mean fixation duration was longer for the landscape composed of 4 species of plants than for the landscape composed of 8 species of plants. The mean fixation duration differences of photomontages showing landscapes composed of 5, 6, 7, and 9 species of plants were not significant. In summary, the mean fixation durations of photomontages showing the different number of species were, in descending order, 4, 5, 7, 6, 9, and 8 species of plants. The total fixation duration was longer for the photomontages showing a landscape composed of plants with conical forms compared to mounding and vertical forms.

**Table 3.** Differences of gaze behavior in vegetation landscape composed of plants of different forms and species richness.

| **Fixation Count** | | | | **Mean Fixation Duration** | | | | **Total Fixation Duration** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Subset** | | | | **Subset** | | | | **Subset** | |
| Species richness | N | 1 | 2 | Species richness | N | 1 | 2 | Plant form | N | 1 | 2 |
| 4 | 177 | 27.14 | | 8 | 179 | 0.2939 | | M-V | 176 | 7.9879 | |
| 5 | 177 | 27.34 | | 9 | 180 | 0.3012 | 0.3012 | M | 178 | 8.0692 | 8.0692 |
| 7 | 178 | 28.17 | 28.17 | 6 | 179 | 0.3177 | 0.3177 | V | 180 | 8.1322 | 8.1322 |
| 6 | 179 | 28.21 | 28.21 | 7 | 178 | 0.3181 | 0.3181 | C-V | 179 | 8.1350 | 8.1350 |
| 8 | 179 | 28.89 | 28.89 | 5 | 177 | 0.3273 | 0.3273 | C | 179 | 8.2152 | 8.2152 |
| 9 | 180 | | 29.34 | 4 | 177 | | 0.3396 | C-M | 178 | | 8.3065 |
| Sig. | | 0.09 | 0.49 | Sig. | | 0.273 | 0.139 | Sig. | | 0.098 | 0.073 |

Note: Harmonic means for groups in homogeneous subsets (α = 0.05) are displayed.

### 3.2. Ratings Used to Assess Landscape Preference

Levene's test result indicated that the questionnaire data met the homogeneity of variance. Tests of between-subject effects indicated that the effects of the plant form were significant for ratings ($p < 0.05$). Post hoc analysis revealed that participants assessed the six groups of planting landscapes differently for preference (Table 4). More specifically, the vegetation landscape composed of mounding plants received the highest ratings (mean = 7.11/10), while the landscape composed of vertical plants received the lowest ratings (mean = 5.28/10). Interestingly, the scores based on the observed means of vegetation landscapes composed of conical plants and plants of various forms were in a homogenous subset. The ratings indicated a clear difference in preference held by participants, with vegetation landscapes composed of mounding plants being preferred to the other forms.

**Table 4.** Differences in aesthetic preference ratings of vegetation landscapes composed of plants of different forms.

| **Preference Ratings** | | | | |
|---|---|---|---|---|
| | | | **Subset** | |
| **Plant Form** | **N** | **1** | **2** | **3** |
| V | 258 | 5.28 | | |
| M-V | 258 | | 6.38 | |
| C | 258 | | 6.42 | |
| C-V | 258 | | 6.48 | |
| C-M | 258 | | 6.51 | |
| M | 258 | | | 7.11 |
| Sig. | | 1.000 | 0.952 | 1.000 |

Note: Harmonic means for groups in homogeneous subsets (α = 0.05) are displayed.

### 3.3. Relationship between the Eye-Tracking Data and Ratings

Boxplots of gaze data metrics show individual fixations on each vegetation landscape photomontage (Figure 6). Spearman's product-moment correlation analysis results indicated a strong relationship between the two types of data collected in Experiment B (Table 5). Regression analysis revealed that there was a significantly positive correlation between fixation count and preference ratings, while a significant negative correlation was found between mean fixation duration and preference ratings (Figure 7). In addition, the results showed a negative correlation between preference ratings and total fixation duration. This finding indicated that for the vegetation landscapes, the preference ratings increased with the fixation count and vice versa. Accompanying this growth in mean fixation duration and total fixation duration, however, was a decline in preference ratings.

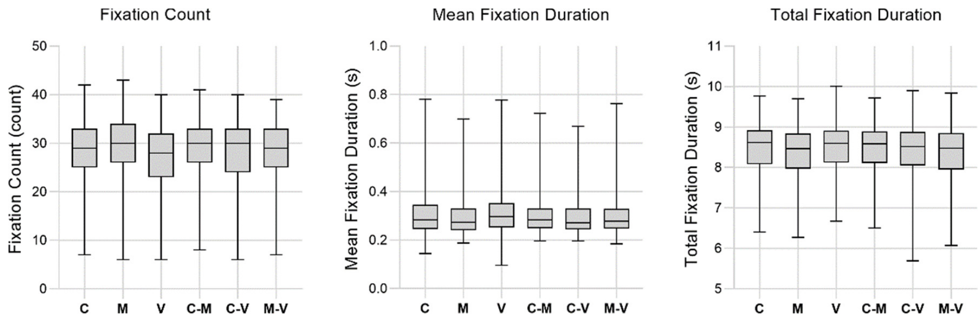


**Figure 6.** Boxplots of fixation count, mean fixation duration, and total fixation duration.

**Table 5.** Spearman's correlation coefficients for aesthetic preference ratings and eye-tracking data.

| | **Landscape Preference** |
|---|---|
| Fixation count | 0.098 ** |
| Mean fixation duration | −0.117 ** |
| Total fixation duration | −0.124 ** |

### 3.4. The Differences in Fixation and Ratings in Terms of Personal Characteristics

The Mann–Whitney test (2 samples) was performed to analyze the influence differences in gaze fixation and ratings in terms of personal characteristics, such as profession (landscape architecture students and others) and gender. The results, as shown in Table 6, indicated that the effects of gender were significant for fixation count and mean fixation duration, while profession showed no significant effect in any of the fixation metrics. More specifically, concerning visiting the photomontages showing vegetation landscape, the women's fixation count was significantly higher than men's, while men's mean fixation duration was longer ($p < 0.05$). Furthermore, there was a significant difference in ratings between professionals and nonprofessionals (nonprofessionals rated higher), while no significant differences were found between men and women.

**Table 6.** Comparison of men and women, professional and non-professional on landscape perceptions and preferences, based on a Mann-Whitney test.

| | **Mean Rank** | | | | | |
|---|---|---|---|---|---|---|
| | **Gender** | | | **Profession** | | |
| | **Men** | **Women** | ***p*** | **Professionals** | **Non-Professionals** | ***p*** |
| Fixation count | 688.08 | 850.47 | 0.000 * | 766.15 | 767.87 | 0.939 |
| Mean fixation duration | 833.07 | 697.11 | 0.000 * | 757.54 | 776.77 | 0.395 |
| Total fixation duration | 772.93 | 760.73 | 0.590 | 753.44 | 781.01 | 0.223 |
| Landscape preference rating | 789.05 | 759.26 | 0.183 | 736.19 | 814.63 | 0.000 * |

Note: * Significant at $p < 0.05$.

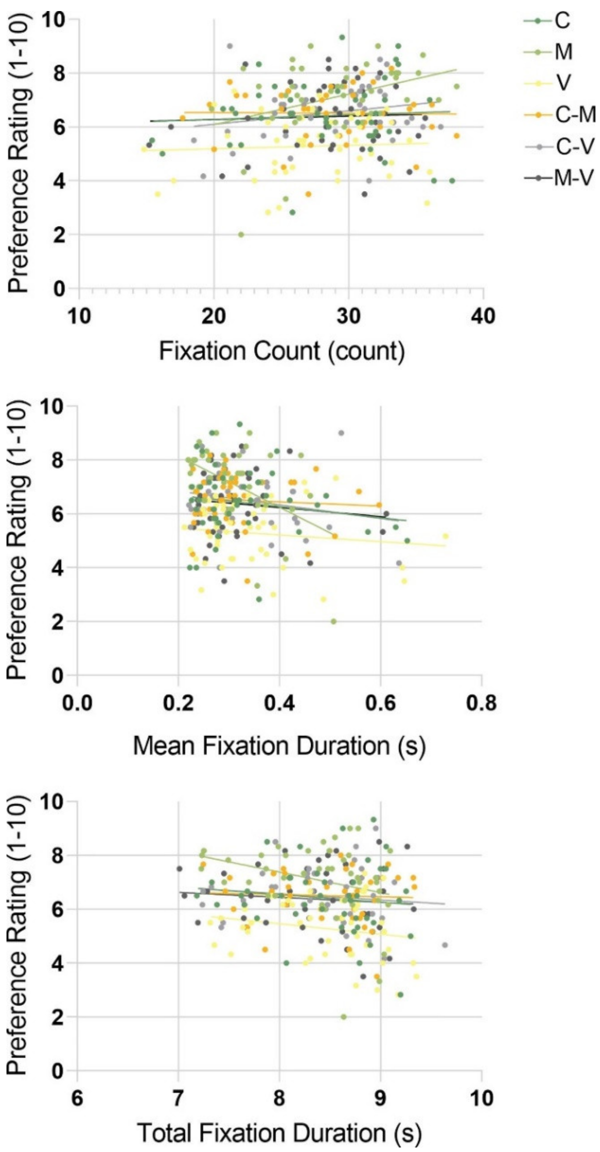


**Figure 7.** Correlations between preference ratings and gaze metrics of vegetation landscapes composed of plants of different geometrical forms.

## 4. Discussion

### *4.1. Plant Form and Species Richness Influence the Gaze Behavior towards Perennial Landscapes*

Plant form is related to formal aesthetics that are concerned primarily with formal sensate properties, such as shapes and complexities of the visual world [20]. Through Gestalt theory, plant forms can be abstracted and simplified to achieve unity and legibility. Yılmaz [21] proposed determining the formal aesthetic quality of plant group silhouettes through the visual properties of plants (forms and texture) and basic design principles. According to similar studies [23,42], the geometrical forms of perennials were summarized in conical, mounding, and vertical forms in our study through the proximity and similarity principles of Gestalt theory, in which general concepts, such as unity, order, and harmony, could be expressed as specific landscape patterns. If properly used, design including formal diversities can provide legible, easily intelligible, and aesthetically pleasurable perennial landscapes. Perceptional differences in plant forms were identified by Eroğlu et al. [43]. The results of this study on landscape photomontages composed of plants with different forms showed that the total fixation duration was longer for photomontages composed of conical plants than for other forms. It seems that the more attractive the plant that has unique flowers or inflorescences is, the longer it is looked at. The perennial combinations that include an upright tendency attracted more fixations. Thus, upright perennials, such as hollyhocks with loosely flowered spikes, can be appropriately applied to the design of parks, gardens, roadside vegetation, and other green spaces to attract more visual attention.

Concerning the three gaze metrics, the findings suggest that species richness was the factor most closely related to eye movements. Landscape heterogeneity, described by the richness and diversity of landscape elements [44], is the principal mechanism through which people perceive landscape structural diversity and is one of the most promising urban green space improvement measures [9,45]. As other studies have shown, the degree of landscape heterogeneity determines how people make eye movements [40]; e.g., less fixation duration and mean fixation duration are generated on highly heterogeneous landscape photomontages [24]. Our study suggests that the photomontages showing high degree of species richness generate more fixation counts. This result is possibly due to humans' innate predilection for exploring and obtaining information [46], and the complex landscape information could elicit more curiosity, thereby possibly leading to more fixations. Species richness with structural properties may eventually prove to be an efficient factor influencing the visual perception of vegetation landscapes. The outcome emphasized the importance of species richness as an element of landscape heterogeneity and aesthetic appreciation [25,47].

One unanticipated finding was that plant arrangement showed no significant effect on gaze behaviors, including fixation count, mean fixation duration, and total fixation duration. It has been generally accepted that landscape arrangement, referring to the spatial characteristics, results from the combinations of different heights of plants [26]. Prior studies have confirmed the significant impact of space on landscape perception and have found a strong relationship between the shape of space and perceived spaciousness [48]. Landscapes with a high degree of openness are associated with longer fixation duration and fewer fixations [40]. Moreover, visual perception in humans is characterized by a strong orientation toward patterned information. We therefore hypothesized that most people, guided by highly structured and ordered landscape space, would produce different patterns of eye movements. However, the results showed that the landscape space formed by plant arrangement had no significant effect on gaze behavior. A possible explanation for this finding might be that the perennial landscape we studied was composed of lower vegetation and had difficulty constructing recognizable perceived spaciousness on a human scale. Some studies have highlighted the key role of plant height in landscape perception [15,49]. Therefore, focusing on plant characteristics, such as form, color and texture, is a significant part of planting design and may help to inspire more visual changes. Future perennial landscape design should pay more attention to plant forms and biodiversity.

### *4.2. Perspectives on Attention Restoration Theory: Aesthetic Preference May Be an Accelerator to Promote the Interaction with Landscape*

Research concerning behavior and aesthetic response associated with visual perception may contribute to understanding human interactions with the natural environment. The results of Experiment B revealed a strong correspondence between unconscious eye movements and the subjective assessment that subjects consciously make. Changes in gaze behavior (e.g., the higher fixation count) while viewing different photomontages were generally accompanied by variances in preference ratings. More specifically, the landscape preference rating was positively correlated with fixation count but negatively correlated with mean fixation duration and total fixation duration. For instance, in our study, the ratings of perennial landscape photomontages composed of mounding plants were highest, meanwhile, the most fixation count was generated on these photomontages. The results reported here appear to support the assumption of the relationship (positive or negative) between the preference ratings of participants and gaze behavior, and these observations confirm previous findings [35,50] that showed that gaze behavior is involved in preference formation.

The differences in eye movement manifest as Kaplan's [51] hypothesized "soft fascination" or what Ulrich [46] calls "initial affective response". Fixation metrics, representing the attention engaged when viewing a landscape, are particularly important in different eye movement measurements [52]. The lower fixation counts for natural landscapes indicated they were viewed with "effortless attention" [53]. Several studies [32,39,54] have revealed that a large number of fixation counts indicated that subjects viewed the landscape with more effort and deliberation. In our work, the observing pattern for the high preference rating is that participants had higher fixation counts. Higher preferences were associated with greater affective restoration [55]. Thus, processing landscapes with higher preference ratings requires greater visual attention; this finding might explain why people recover from stress and replenish their energies by having more fixation counts while viewing landscapes of higher preference. Additionally, a negative correlation was found between mean fixation duration and landscape preference in this study. Cottet et al. [32] and Franěk et al. [54] pointed out that there might be an association between the naturalness of the landscape and mean fixation duration. The outcome further clarified the statistical relationship between mean fixation duration and landscape preference, and future studies should establish a regression model for predictive analysis. In addition, we found a negative correlation between total fixation duration and landscape preference ratings possibly because a longer fixation duration means more difficulty in extracting information from landscape photomontages, thus hampering landscape legibility. The lower legibility of the landscape may arouse negative feelings and thus influence an individual's aesthetic preference. People's preferences for the environment are influenced by their perceptions of the environment's potential to provide restoration from stress [55]. Multiple ways of visual contact with nature are important to trigger varying degrees of restorative responses. In other words, vegetation landscapes created on the basis of public aesthetic preferences have positive implications in moderately capturing involuntary attention and thus providing restoration from stress or fatigue.

Our study reported a correlation between landscape aesthetic preference and gaze behavior. The finding accorded with Cottet's findings [32], which were obtained in "real-world" conditions. The author's findings showed that gaze behavior might be considered an efficacious indicator of landscape quality evaluation. Although these findings cannot be extrapolated to all types of landscapes, our experimental studies still provide further support for unraveling the environmental behavior and their links to restorative experiences. The Eye-tracking technology may be more readily applied by landscape architecture designers and other decision-makers in design, establishment, and management.

### *4.3. Demographic Profile*

This exploratory study analyzed whether demographic differences influenced the perception of and preference for perennial landscapes, and the results are not entirely consistent with those of prior studies. The overall results indicated that the fixation count and mean fixation duration of participants of different genders toward the photomontages showing viewed vegetation landscapes were significantly different; furthermore, women had more but shorter fixations than men. Therefore, these female participants possibly observed more extensively and viewed the vegetation landscapes in more detail than male participants. The observed difference in aesthetic preferences between men and women in this study was not significant; although these results differ from some published studies [29,56], they are broadly consistent with Paraskevopoulou's [41] findings, which used flower or shrub combinations as stimuli and showed that gender differences between participants did not affect their preferences. Concerning the former, this inconsistency may be due to the high complexity of landscape compositions that include roads, trees, shrubs, and herbaceous plants, whereas the focus was perennials in this study.

Since our results showed no significant differences between professionals and nonprofessionals in gaze behavior, the group differences found by DuPont et al. [57] were probably because participants were not given certain top-down tasks. In addition, during the viewing of the photomontages, compared with professionals, nonprofessionals tended to give strongly higher ratings. Individuals' expertise in landscape design apparently affects individuals' preference for plantings landscapes, thus suggesting that educational efforts might be effective in improving landscape quality based on group preference [58,59]. In some cases, familiarity with relevant expertise possibly creates an adjustment to particular levels of stimulation, thereby influencing the landscape preference in aesthetic experience. Overall, the subjects' variance in the landscape evaluation studies may have different origins related to sociocultural [60] or psychological [59] factors that affect landscape preference. In particular, a recent study by Tam and Milfont [61] emphasized cultural influences on aesthetic preference and provided a culturally informed view of the relationships between humans and environments. If designers rely exclusively on consensus aspects, characteristic features remain ignored. Thus, personal attributes as potential determining factors of viewing behavior should be considered important in landscape design.

### *4.4. Future Perspectives*

Several limitations need to be considered in future studies. The first limitation is that gaze behavior may be affected by plants with different colors, although the impact of colors on visual attention was relatively minimized by combining adjacent colors to form harmonies and unities in each plant composition. However, the focus of the formal aesthetic characteristics of plants studied in this paper was on plant forms rather than colors, which could be further considered in follow-up research works. Another limitation is that instead of real-world landscapes, a variety of photomontages were used as experimental materials. In the real world, landscape perception resulting from multisensory contributions is generally considered a dynamic process. However, on-site data acquisition based on the real landscape is subject to many interferences occurring on a cyclical or casual basis, e.g., bird flight or maintenance of vegetation [32]. As in previous studies [29,41,62], the influences of external variations were controlled by using photomontages modified in the same particular way. Future research can use more realistic and precise landscape visual features to break the spatiotemporal constraints and uncertainties of on-site experiments. Notwithstanding these limitations, the findings based on photomontages and eye-tracking technology will probably be applicable to real environments in the future and make several contributions to the field of planting design and environmental behavior. The possibility for future research would be to investigate how to build a landscape preference prediction algorithm model driven by the perceived value of multidimensional eye movement data; this model can be used to evaluate landscape preference with a highly complex scenario without any concern about misleading results that people make under the influence of social roles or other restrictiveness. It will become increasingly common to use behavioral models to incorporate aesthetic preference into design and planning decisions.

## 5. Conclusions

This study has demonstrated, for the first time, the influence of the formal aesthetic characteristics of perennial landscapes on gaze behavior based on Gestalt theory. We considered three aesthetic characteristics (plant forms, species richness, and plant arrangement) in vegetation landscapes and studied the impact of their compositions on landscape perceptions. The results showed that plant form was significantly related to mean fixation duration, while plant arrangement had no significant relationships with any gaze metrics. We also found that with the increase in species richness, the number of fixations increased, while the mean fixation duration decreased. Therefore, paying attention to biodiversity and plant characteristics, such as form, color and texture, may help establish a promising landscape from the perspective of eco-aesthetics and inspire more visual changes. Additionally, to advance knowledge in aesthetic preference, we compared the physical measurements of gaze behavior and the preference ratings. The results suggested that the rating of landscape preference was positively correlated with fixation count but negatively correlated with mean fixation duration and total fixation duration. This study confirms previous findings and contributes additional evidence that suggests that in the context of landscape perception and restoration, public preferences in guidelines for landscape management and spatial planning deserves further consideration.

**Author Contributions:** Conceptualization, Y.S. (Yangyang Shi) and Y.X. (Yiping Xia); methodology, Y.S. (Yangyang Shi); software, Y.S. (Yangyang Shi); validation, J.Z., X.S. and L.C.; formal analysis, Y.S. (Yangyang Shi) and J.Z.; investigation, Y.S. (Yangyang Shi), X.S. and L.C.; resources, R.F.; data curation, Y.S. (Yangyang Shi); writing—original draft preparation, Y.S. (Yangyang Shi); writing—review and editing, J.Z. and Y.X. (Yiping Xia); visualization, X.S. and Y.X. (Yunchen Xu); supervision, Y.X. (Yiping Xia); project administration, Y.S. (Yang Su); funding acquisition, Y.X. (Yiping Xia) All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** We gratefully acknowledge the Experimental Teaching Center of Media Communication of Zhejiang University for the research technical support and eye-tracking equipment. We also wish to thank all people who took the time to participate in our study, and who provided language help and writing assistance including Lin Qiao, Jingwei Zhuang, Tong Xu, and Cong Gao.

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

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