Article

Resolution Aspects for Near-Field Projections

Alexander Stuckert [1,2,]* **and Tran Quoc Khanh [1]**

1   Laboratory of Adaptive Lighting Systems and Visual Processing, Technical University of Darmstadt, Hochschulstr. 4a, 64289 Darmstadt, Germany
2   BMW Group, Knorrstr. 148, 80788 Munich, Germany
*   Correspondence: alexander.stuckert@bmw.de

Abstract: This work intends to define the resolution requirements for near-field projections in a psycho-physical study design to evaluate the participants' perception under the influence of different ambient lighting levels and various viewing distances. The variation in ambient lighting and viewing distances relates to various daytime and critical distances in urban environments. The application of near-field projections increases the popularity of communication- or safety-relevant projections, such as for automated vehicles. However, previous studies in the filming industry have shown that the resolution requirements differ depending on the application. In this work, a field study design presents an experimental approach to define a perceived resolution on the street surface in the near field around the vehicle. Furthermore, the study evaluates the influence of viewing distance, ambient lighting and projection content on the perceived resolution in detail. The results reveal a significant dependency on ambient lighting ($p < 0.05$). Furthermore, this work states that the symbol-based projection has lower resolution requirements, e.g., a viewing distance of 1 m and 3 m results in a 2 pixels per degree resolution compared to the text-based projection in the parking garage scenario. Nevertheless, in the dusk/dawn scenario, the perceived resolution can be grouped for viewing distances above 1 m for content-independent projections.

Keywords: near-field projections; resolution; ambient luminance; projection content; logistic regression; human-centric lighting; interactive design

1. Introduction

Projections are widely used in several fields of application nowadays, such as the film industry, consumer electronics and the automotive industry. Nevertheless, all fields have specific challenges or advantages when looking at projection technologies. In the future, mobility concepts or technology automated vehicles will be dominant. No matter how long the transition phase from manually driven to automated vehicles will take, it is crucial to define and evaluate technologies for these types of mobility. Therefore, the automotive sector will play a significant role in future communications technologies such as projection- or display-based communication with other non-automated road users.

In the automotive sector, near-field projections or displays are used to show graphical or informative content around the vehicle to welcome the vehicle user with a message or design-driven pattern. Additionally, near-field projections or displays can inform the vehicle user with vehicle-based information, such as the battery status of an electric vehicle, or situation-based content, such as weather information at the trip's destination. Both technologies are considered for communication for highly automated vehicles with other road users (RUs). However, projection-based communication has an advantage compared to display-based methods since a safety-relevant projection can be placed in the field of view of other RUs, e.g., a projected turn indicator to warn an upcoming cyclist of a turning vehicle.

In general, digital projectors are widely used in different sectors, such as consumer electronics, film and automotive industries. Every application field targets a positive

experience for the user. However, environmental factors, which influence the projected content, vary depending on the application sector. For example, the various requirements in the automotive industry are diverse when projections are applied in the interior with curved projection surfaces [1] or in the vehicle's exterior while projecting onto the street's surface [2–12]. In addition, several properties depend on the application sector, which is essential for research: contrast, brightness, resolution and others. Finally, an important aspect is a necessary resolution on the projected surface to generate a sharp and high-quality image. This factor gains importance, especially when looking at pixel-based digital projection technologies, where an LCD, LCoS, DMD, or μLED is used as an imager [13–15].

Besides decorative or design-related near-field projections next to the vehicle, another important application field is the safety-relevant projection content, which is crucial for other RUs, e.g., pedestrians and cyclists, especially in an urban environment. Current research focuses on the unambiguity, understanding and detection of the different projection content and where it will be illustrated [4,8,16–19]. However, the research still needs to examine the required resolution from the pedestrian's perspective, which, on the one hand, is crucial in perceiving the illustrated projection content (symbol- or text-based message). On the other hand, the resolution is relevant for decisions on the projection technology and, therefore, the resulting use cases [4,8,9,12]. Namyslo et al. focused on the use case of cyclists, which are warned by a near-field projection (amber arrow sign) of a turning vehicle in a dusk scenario. Afterward, 19 participants provided a subjective opinion, where 86.8% of the subjects understood the intention of the turning vehicle better with the turn indicator projection compared to the situation with no illustrated projection [4].

Additionally, several influencing factors affect the observer's perception when interacting with a near-field projection. There are two main influence areas for the perception of near-field projections. First, the participant's personal factors influence visual acuity [20–23]. The visual acuity influenced by age plays a significant role in general traffic. Sivak and Schoettle's examination illustrates an increase in older drivers in eight countries worldwide: the United States, Sweden, Norway, Great Britain, Canada, Japan, South Korea and Germany [23]. Second, Bleecker et al. provide a study on the impact of age and sex on simple visual reaction times. The results state that age significantly influences the reaction times for participants older than 70 years. Additionally, the comparison shows a sex difference [20]. Henceforth, this indicates the importance of focusing on the older population for visual tasks in the context of future mobility concepts in urban environments.

Second are environmental factors such as adaptation luminance, the projection surface, or viewing distance [12,24–28]. In detail, the relationship between viewing distance, the resulting screen size and visual acuity has been under evaluation for several years for conventional displays or projection-based screens [24,26–28]. Previous research from the television or physiology sector indicates the preferred viewing distance and screen size when viewing an image or video [26–28]. Additionally, the impact of the adaptation luminance is stated by Shlaer, as the findings illustrate that visual acuity varies with different adaptation luminance due to the interaction of cones and rods on the retina. Furthermore, the tested target shape influences visual acuity and the resulting detailed perception [28].

Moreover, Lund discovered in his experiments in television research the correlation between viewing distance and the resulting screen size. Like Jesty, Lund had his participants set their optimal viewing distance for themselves in the various experiments [26,27]. Both researchers, Jetsy and Lund [26,27], varied the image size and/or the resolution. A point of criticism is that Lund mixes certain influencing factors without considering their effect, for example, using different screen technologies (conventional display or projection screen) or changing the ambient lighting within the experiments [27].

Consequently, when mixing the methods and drawing a correlated conclusion, Lund's results must be considered with caution, and are saturated at increasing viewing distances due to decreasing visual acuity [27]. However, this outcome corresponds to the results of Jesty [26]. Furthermore, Lund lists possible influencing factors crucial for the experimental

setting, such as screen resolution, ambient lighting, video content and the participants' mindset [27]. Further, Viršek mentions that the various projection surfaces, like the different granularity of the asphalt, limit the image quality which an observer perceives when looking at a near-field projection [12].

It is necessary to examine the requirements for near-field projections in the automotive sector, especially for safety-relevant projections with potential differences for either text- or symbol-based projection content and the influence on the observer's perception of various lighting conditions. In this work, two subject studies present an experimental approach to defining an effective resolution on the street's surface in the near-field around the vehicle under two different lighting levels. Hence, the forced-choice method is used in the subject studies to collect the necessary data for subjective opinion regarding the resolution requirements for a high-quality projection. Consequently, logistic regression is applied to the data to evaluate thresholds for the perceived resolution and, finally, to establish resolution requirements for near-field projections.

To the best knowledge of the author, the reported experiments are the first to systematically study repeatedly the impact on human perception by road-/near-field projections for either safety- or design-driven purposes. Additionally, this research determines the importance and relevance of the near-field projections projected around the vehicle in no matter which direction, since the field studies generally asked for any perception corresponding to the near-field projections. Therefore, this work is organized as follows: Chapter 2 delivers an overview of the field study, its procedure, methods and analysis relating to the used materials and methods of this field study. Further, Chapter 3 reports the results of the field study in detail, including the statistical analysis. Chapter 4 discusses and summarizes the paper in an encompassing way with its main findings. Finally, a brief conclusion with an additional outlook for further research is given in the last chapter.

2. Materials and Methods

This field study will apply the methods of constant stimuli, a standard measure in psychology, to define physical measurements. Therefore, first, the participants collectively will be described in detail. Further, the field study and its procedure are illustrated, as in Figure 1A and the following text, with necessary theoretical background information. Finally, the analysis, which includes logistic regression, is carried out to evaluate the perceived resolution of the participants in pixels per degree (px/°) and the theoretical background for this.

2.1. Participants

The participant collective consists of two independent studies: 70 subjects (19 female, 51 male) of internal workers from different departments of BMW Group in Munich, Germany, between 21 and 59 years (M = 34.86, SD = 10.75) participated in the field test. 56% of the participants used a visual correction aid, while 77% of the subjects specified that they were short-sighted. In the second field test, 25 participants (9 female, 16 male), also internal workers of the BMW Group in Munich, Germany, ranging from 20 to 58 years (M = 35.68, SD = 11.82), participated. Additionally, 48% of the subjects used a visual correction aid to correct their shortsightedness, because 92% were short-sighted.

2.2. Subject Study Setup

To establish an equal subject study environment for all participants, the setup in the light channel is characterized in detail. First, two projection contents were selected for the experimental design: symbol- and text-based content (Figure 1B,C). The graphic illustrates a loading battery symbol (68.5 cm wide and 40.5 cm high) (Figure 1B) and the text 'Welcome to Munich' used the front style Helvetica (93 cm wide and 37.5 cm high) (Figure 1C). Good legibility is the main requirement for a typeface. For this purpose, DIN 1450, for example, specifies the number of criteria [29]. These include typeface, stroke width and thickness and character spacing. However, the symbol-based content or the smallest letter of the

text-based projection is designed to fulfill DIN 3864 [30] and guarantee the text's legibility even at a viewing distance of 5 m. Therefore, this results in the used projection sizes of the text or graphics in these tests.

Second, the adaptation luminance in the testing room was characterized at 1 m, 3 m and 5 m away from the projection area to guarantee a homogenous ambient lighting condition (Figure 1A). Therefore, in the following work, the scenario with 191–263 lx ambient illuminance is called dusk-/dawn-scenario (DDS), which is the scenario of interest in the first study. This represents the daily usage of a vehicle when the user is leaving for work or coming back home. Of interest in the second study was a scenario with 20–25 lx ambient lighting, which matches the regulation for parking lots with high traffic volume [31], called the parking garage scenario (PGS).
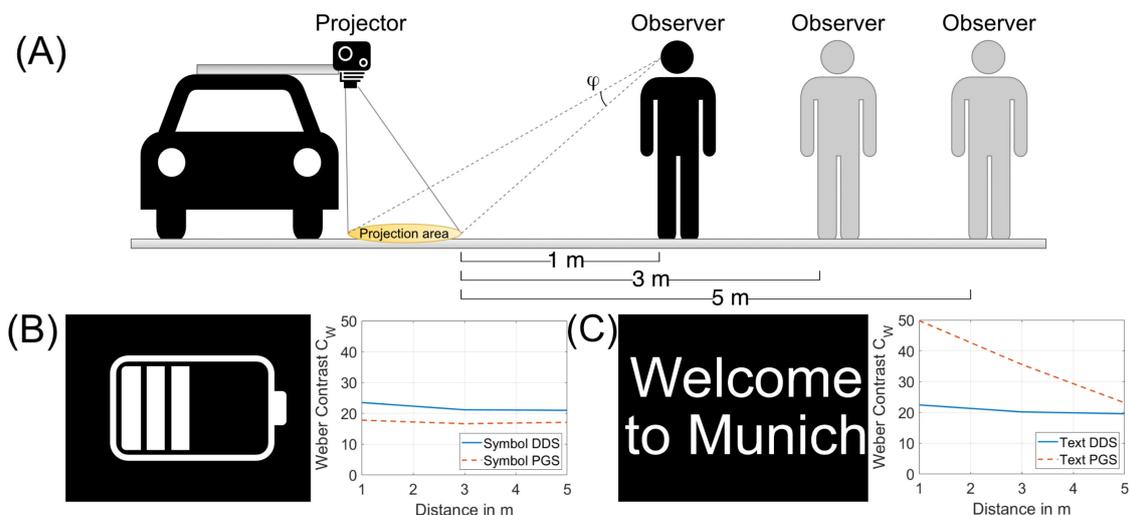

Figure 1. Schematic illustration of the experimental setup and used projection content in both studies. (**A**) The experimental setup for both studies, where a 3LCD laser projector [32] is mounted on a vehicle, indicates the three different viewing distances of 1 m, 3 m, or 5 m. Additionally, the observer's viewing angle to the projection area for the 1 m viewing distance is illustrated. (**B**) Display of the symbol-based projection content and a graph with the contrast measurements in PGS and DDS related to the viewing distance. (**C**) Picture of the text-based content and the graph for the corresponding contrast in PGS and DDS related to the viewing distance.

Further, it is crucial to ensure a constant Weber contrast, so that the participants will not be influenced by the perceived Weber contrast C_W, which is shown by Equation (1):

$$C_W = \frac{L_{Projection} - L_{Background}}{L_{Background}} \tag{1}$$

where $L_{Projection}$ states the luminance of the projection and $L_{Background}$ is the background luminance of the street's surface [33]. Consequently, the contrast in the dusk/dawn scenario ($19.60 \leq C_{W,dusk/dawn} \leq 23.53$) varied slightly no matter what projection content (Figure 1B,C). In the parking garage scenario, the contrast for the battery symbol was constant ($16.66 \leq C_{W,parking,battery} \leq 17.81$) (Figure 1B) though the text message showed a decreasing trend for increasing viewing distance ($23.16 \leq C_{W,parking,text} \leq 49.82$), which is displayed in the graph in Figure 1C. All contrasts were measured from a first-person perspective with a luminance camera at the three viewing distances and with a measuring height of 1.72 m, which represents an average German person [32], resulting in different viewing angles on the projection area in the analyzed measurements (Figures 1A–C and 2B,C). The viewing angles range between 59.83° at 1 m (see Figure 1A) to 18.98° at 5 m viewing distance, assuming an average German person [34]. Therefore, the contrasts are valid for the used projection surface, which is smooth and fine-grained asphalt with a luminance

coefficient of 0.03 in the light channel in PGS and DDS (Figure 2A). Additionally, a classification of the angle-dependent reflection behavior S according to the CIE standard was made, which corresponds to a diffuse scattering surface (S < 0.4) for the PGS (S = 0.09) and DDS (S = 0.09) scenario [35]. A post-study questionnaire asked the participants if any glare was perceived during the testing procedure to ensure that the study environment was appropriately defined for all subjects. The results of this question for the DDS and PGS are displayed in Figure A1. These assure that the subjects do not perceive glare, as none of the subjects stated so in the questionnaire responses.
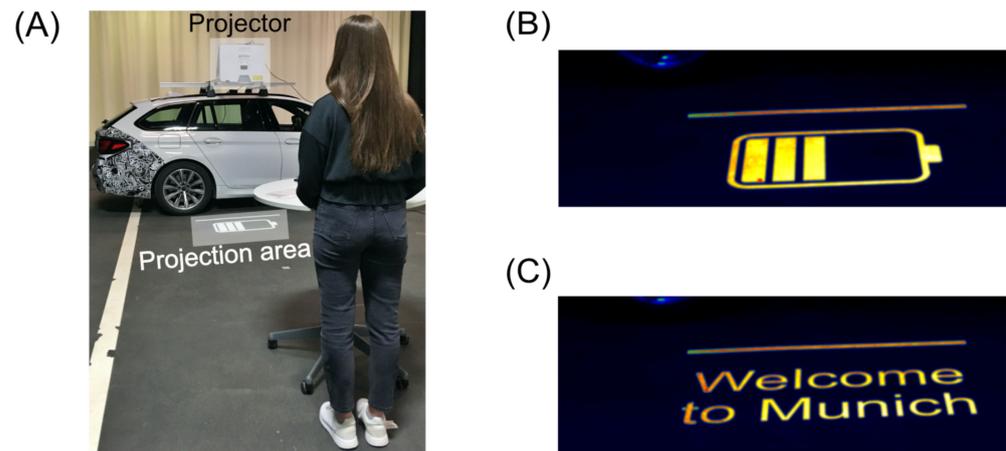

Figure 2. Extract of the study and examples of luminance measurements. (**A**) Participant at 3 m observation distance to the projection area in the DDS. The observed projection content consists of the battery symbol on the fine-grained asphalt. (**B**) Luminance measurement of the symbol-based projection in the PGS from a first-person viewing perspective of 3 m [34]. (**C**) Luminance measurement of the text-based projection in the PGS from a first-person viewing perspective of 3 m [34].

Furthermore, to ensure that the projection surface is suitable for evaluating projection qualities, a pre-study took place to evaluate the smallest resolvable detail on the street's surface. The subjects' task was to confirm whether they could see one or two lines where eight different gap widths were repeated randomly three times, corresponding to the constant stimuli method. This procedure was the same for the PGS and DDS scenarios at a viewing distance of 1 m, which is the most critical viewing distance from which to evaluate the smallest resolvable detail. The smallest resolvable detail relates to a standard visual acuity test task, such as a Landolt ring task [36]. In the subject study, the line pairs rotated 45, 90, or 180 degrees, so subjects would have a variation and thus no learning effect during the study. Eight subjects between 27 and 60 years participated in the pre-study. The resolution of the gap between the two lines was 85.73 px/° for PGS and 52.93 px/° for DDS.

Consequently, every participant had about 10 min to adapt to the ambient luminance in every scenario, which guarantees the activation of the rods in their sensitivity [36], so the illustrated projections do not discomfort the subject. The participants used a modified keyboard, where just the keys N and Y were accessible, since the other keys were removed. Finally, after the introduction, the participants had to log in their subjective answers by pushing the key Y when perceiving a high-quality resolution and pressing the key N if the quality did not meet individual quality requirements. The keyboard is connected to a computer via a USB cord to guarantee no potential latencies. The visual stimulus presentation and data handling is implemented in Matlab R2018b with the graphical toolbox Cogent 2000 version 1.33 [37]. All instructions, experiments and the questionnaire used the German language.

The study design was mixed between-within-design with ambient lighting being the between-subjects-factor and the projection content and viewing distance being the within-subject-factors.

2.3. Testing Procedure

The two collectives consisted of different participants. The second study was conducted three months after the first, but the testing procedure was identical. All participants participated within two weeks in a single 30-min-session.

The testing procedure for both studies was identical: first, the participants read an instruction sheet while the experimenter adapted the ambient luminance of the respective scenario. Before the test started, examples of the high and low resolution of every projection content were shown to the participants, which were not included in the testing set. The examples ensured that every participant had a similar prior perceptual threshold due to different individual experiences of near-field-projections. Second, the participants got used to the test procedure with a test run (Figure 3A). To prevent learning effects, ten different pre-set image qualities that occurred three times in the total set were presented in a random order (Figure 3B), resulting in a total of 30 images per sequence, and participants had 2.5 s to log in their decision whether the displayed projection had a good or bad resolution in reference to the displayed examples in prior testing. The presentation time of every projection was 2.5 s (Figure 3A). The experiment followed a forced choice procedure of constant stimuli [33,38–40]: while focusing on the projection area, the participants had to either press 'Y', if the displayed quality of the projection had a high quality, or 'N' if not. There was a random delay from 0.5 to 1 s between sequences to prevent learning effects. After the delay, visual feedback was displayed if the answer was logged in successfully. The participants rated the projection's quality subsequently from one of the three testing distances, e.g., 1, 3, or 5 m. The order of distances was randomized between participants. The same procedure was repeated for both projection contents (text- or symbol-based), resulting in a total of 180 potential ratings of perceived projection quality per participant (10 qualities × 3 repetitions × 3 viewing distances × 2 projection contents) (Figure 3B). Finally, a questionnaire was answered with general personal information and questions about near-field projections. However, the questionnaire analyses are not part of this paper [10].
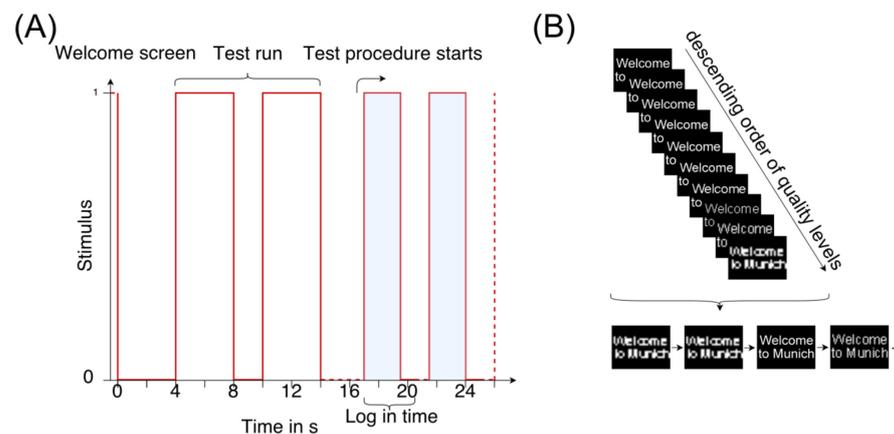

Figure 3. Schematic illustration of the testing procedure and used data set in both studies. (**A**) Visualization of the testing procedure including the welcoming screen, test run phase and the test procedure phase. The stimulus illustrates a projection appearing on the projection area. In addition, the log-in time is displayed with shading in the test procedure. (**B**) Display of all ten different quality levels of the displayed pictures in descending order of quality. Additionally, an example of the possible test procedure output is displayed after applying the randomization algorithm to the data set of 30 images (10 qualities × 3 repetitions) in the lower part of (**B**).

2.4. Data Analysis

The data analysis applied a logistic regression by using the function (Equation (2)) which was introduced by Harvey [41] and Linschoten et al. [39]:

$$P(x) = \gamma + (1 - \gamma) \cdot \left(\frac{1}{1 + \left(\frac{x}{\alpha} \right)^{-\beta}} \right) \tag{2}$$

This logistic regression function was influenced by three parameters: α specifies the stimulus (e.g., the image quality) at the 50% probability level within the range of possible solutions (quality level), the steepness of the function was described by β and the likelihood of correct answers by chance, such as mistyping, was considered by γ. In both studies, the assumption of $\gamma = 0$ was applied to the analysis since the study design and the type of stimuli ensured no random or false answers regarding the subjectively perceived image quality. Therefore, a simplified logistic regression Equation (3) resulted in:

$$P(x, \gamma = 0) = \frac{1}{1 + \left(\frac{x}{\alpha} \right)^{-\beta}} \tag{3}$$

This simplified logistic regression function was fitted to the collected data of the presented stimuli and the corresponding responses from the forced choice method. The presented stimuli represent the different resolution levels projected on the street's surface and correspond to the x-data in the formula above. The $P(x)$-values are the related responses of the subjects to the perceived resolution levels. The values of α and β were determined by using the Matlab curve fitting toolbox independently for every specific scenario in the applied testing condition. The input for finding the values of α and β included the x and $P(x)$ raw data to fit the logistic regression.

Statistical analysis used a chi-square-test, which were calculated to evaluate a 5% significance level by comparison with the critical values of the chi-square distribution [42]. The chi-square-test was used to indicate and evaluate the dependencies for the perception regarding the influence of the ambient lighting, viewing distance influence and influence of displayed content.

3. Results

Before analyzing every data set of the forced choice experiment with logistic regression, a statistical analysis was applied to check the dependencies for the following aspects, such as the observer's viewing distance, the influence of the ambient lighting of the two different scenarios DDS and PGS and the projection content.

3.1. Dependency Analysis of Viewing Distance, Ambient Lighting and Projection Content

Table 1 shows all results of the chi-square tests and the corresponding effect size. Cramer's V is calculated to indicate the effect size of the difference and is categorized by Cohen's effect size benchmark [43]. In the PGS, only one case is significant, where the symbol-based projection is significantly different, with a small effect when the observer evaluates the projection from either a 1 m or 5 m viewing distance. All other combinations regarding the PGS for text- or symbol-based projections are not significant. This leads to the result, without respect to the resolution's values, that in the PGS the viewing distance of the text-based projection can be accumulated to one group regarding the distribution of the participant's answers.

Table 1. Effects of viewing distance, ambient lighting and projection content statistically analyzed with a chi-square test and the corresponding effect size (Cramer's V).

Scenario	Compared Items	Text	Symbol
Distance PGS	1 m × 3 m	$\chi2(9) = 2.53$, $p > 0.05$, V = 0.06	$\chi2(9) = 4.29$, $p > 0.05$, V = 0.07
	1 m × 5 m	$\chi2(8) = 15.09$, $p > 0.05$, V = 0.13	$\chi2(9) = 18.48$, $p < 0.05$, V = 0.14
	3 m × 5 m	$\chi2(9) = 11.89$, $p > 0.05$, V = 0.11	$\chi2(9) = 9.71$, $p > 0.05$, V = 0.10
Distance DDS	1 m × 3 m	$\chi2(8) = 16.72$, $p < 0.05$, V = 0.10	$\chi2(9) = 16.96$, $p < 0.05$, V = 0.09
	1 m × 5 m	$\chi2(8) = 72.43$, $p < 0.05$, V = 0.19	$\chi2(9) = 68.47$, $p < 0.05$, V = 0.17
	3 m × 5 m	$\chi2(8) = 32.74$, $p < 0.05$, V = 0.12	$\chi2(8) = 22.39$, $p < 0.05$, V = 0.10
Ambient Lighting	1 m PGS × 1 m DDS	$\chi2(8) = 30.39$, $p < 0.05$, V = 0.17	$\chi2(9) = 29.70$, $p < 0.05$, V = 0.14
	3 m PGS × 3 m DDS	$\chi2(9) = 24.19$, $p < 0.05$, V = 0.13	$\chi2(8) = 20.72$, $p < 0.05$, V = 0.11
	5 m PGS × 5 m DDS	$\chi2(8) = 17.01$, $p < 0.05$, V = 0.10	$\chi2(9) = 21.79$, $p < 0.05$, V = 0.11
		PGS	DDS
Projection Content	Text 1 m × Symbol 1 m	$\chi2(9) = 5.73$, $p > 0.05$, V = 0.08	$\chi2(9) = 15.65$, $p > 0.05$, V = 0.09
	Text 3 m × Symbol 3 m	$\chi2(9) = 10.49$, $p > 0.05$, V = 0.11	$\chi2(8) = 23.23$, $p < 0.05$, V = 0.11
	Text 5 m × Symbol 5 m	$\chi2(9) = 11.53$, $p > 0.05$, V = 0.11	$\chi2(8) = 23.96$, $p < 0.05$, V = 0.10

Furthermore, all combinations are significant in the DDS with a small effect ($V \leq 0.3$) [43]. Consequently, all answer distributions in the DDS, are significantly different from the other with a small effect size. Likewise, in the comparison in the DDS, the ambient lighting influences the participants' answers, so all combinations for the compared distributions are significant.

Moreover, comparing the distributions of the text- and symbol-based projections within the PGS, the applied chi-square tests are not significant. Hence, there is no difference in the participants' evaluation of the PGS for the projection content. This does not conclude in any difference in the perceived resolution [44]. In addition, the text- and symbol-based content at a 1 m viewing distance for the DDS is not significant, but the combination in the DDS of text- and symbol-based projections at 3 m or 5 m viewing distance are significant. Therefore, these two combinations regarding the projection content are significantly different and must be examined separately in further analysis.

After all, the chi-square analysis features a significant dependency of the DDS independent of text- or symbol-based projection content on the viewing distances. Additionally, the ambient lighting plays a significant role in the subject's evaluation of the perceived resolution in all tested combinations. However, occasional significance is observed in the dependent variables of the PGS with symbol-based projection content (1 m × 5 m), or the projection content comparison in the DDS for 3 m and 5 m. Overall, the chi-square test depicts the dependency of the compared distributions with small effect, therefore, the perceived resolution is evaluated and stated along with logistic regression in detail in the following section.

3.2. Analysis of the Perceived Resolution

The studies executed in this work enhance the current awareness of near-field projections by focusing on the impact of projection content, viewing distance and various ambient

lighting concerning the perceived resolution. Henceforth, the resolution is specified in pixels per degree (px/°) to ensure a technology-independent specification for the effective resolution on the ground by considering the average height of the participants (DDS: 1.79 m; PSD: 1.77 m). Thereupon, the average height of the subjects h of each study, the viewing distance d for either 1 m, 3 m, or 5 m and the calculated resolution of the logistic regression DPI define the effective resolution RES on the ground:

$$RES = \frac{1}{\tan^{-1}\left(\frac{25.4\ mm}{DPI_{Log.Reg.}} \cdot \sqrt{h^2 + d^2}\right)} \tag{4}$$

Before the application of the equation above, the 90% threshold level is extracted from the continuous logistic regression $DPI_{Log.Reg.} = \alpha \cdot \sqrt[-\beta]{\frac{1}{0.9} - 1}$ to achieve the corresponding effective resolution *RES* on the ground, which is illustrated in Table 2 for all possible combinations of viewing distance, projection content, or ambient lighting (PGS, DDS). For every combination, the corresponding confidence intervals are included in brackets to display the lower bound (left number) and the upper bound (right number) of the perceived resolution in pixels per degree.

Table 2. Effective resolution on the ground for a 90% threshold level evaluated by the participants for text- or symbol-based projection content under different adaptation luminance levels defined in pixels per degree (px/°). The numbers in brackets indicate the confidence intervals of 95%, with the lower bound as the first number and the higher bound as the second number of the perceived resolution on the street for every distance, ambient lighting and projection content.

Resolution (px/°)	1 m	3 m	5 m
Symbol PGS	18.70 (18.12; 19.84)	29.45 (28.71; 30.86)	39.62 (38.35; 42.12)
Text PGS	20.89 (20.11; 22.45)	31.70 (30.64; 33.93)	47.46 (46.07; 50.31)
Symbol DDS	25.41 (24.78; 26.34)	40.71 (39.53; 42.46)	52.62 (51.34; 54.50)
Text DDS	31.72 (30.92; 32.88)	39.92 (39.05; 41.22)	51.40 (50.14; 53.30)

The detailed logistic regression is displayed in Figure 4a,b for the PGS's symbol- and text-based projection content. The graphs also include the study's raw data to which the logistic regression (Equation (3)) is fitted for the viewing distances of 1 m, 3 m and 5 m. The 90% threshold is equivalent to the 90% value of the satisfaction probability, displayed for all combinations in Table 2.
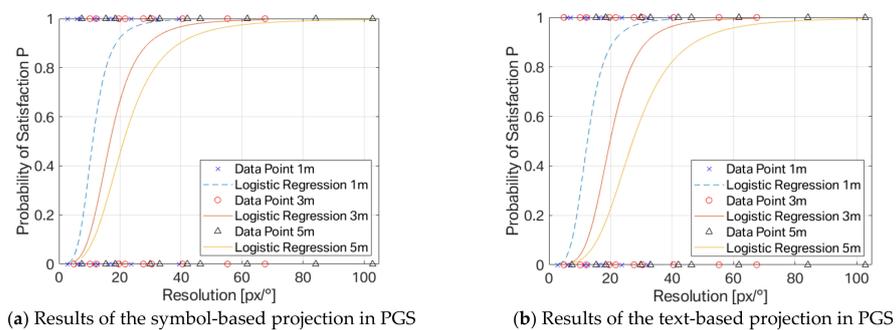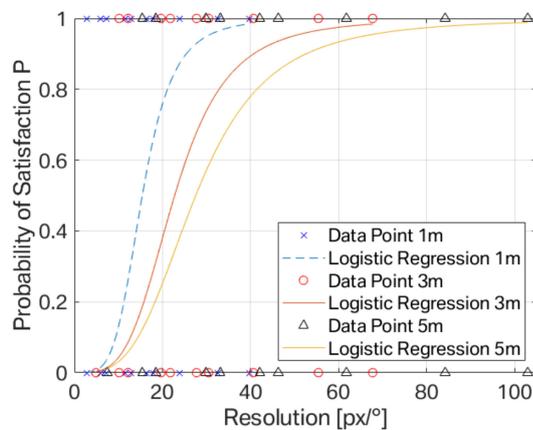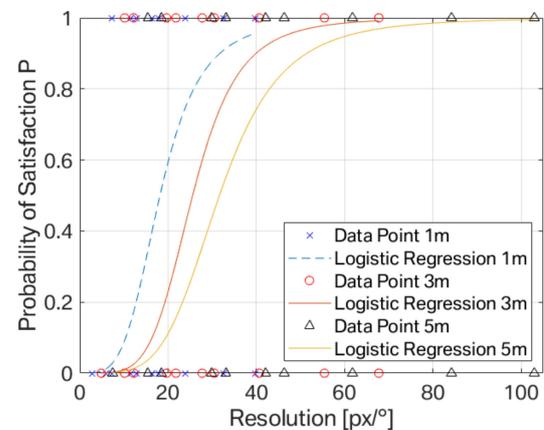

(**a**) Results of the symbol-based projection in PGS

(**b**) Results of the text-based projection in PGS

Figure 4. Results of the analyzed data by using the logistic regressing Equations (3) and (4) for extracting the 90% threshold for the resolution in px/° with the corresponding probability of satisfaction in the PGS. (**a**) Detailed illustration of the logistic regression of the symbol-based projection in the PGS, including the raw data, which is marked with "X" for 1 m data, with circles for 3 m data and triangles for 5 m data; (**b**) Detailed logistic regression of the text-based projection in the PGS including the raw data, which is marked with X for 1 m data, with circles for 3 m data and triangles for 5 m data.

Furthermore, Figure 5a,b display, similar to Figure 4a,b, the study data points at 1 m, 3 m and 5 m viewing distances. The resulting logistic regression for each viewing

distance for the symbol- and text-based projections in the DDS is displayed in the graphs in Figure 5a,b.

(**a**) Results of the symbol-based projection in DDS

(**b**) Results of the text-based projection in DDS

Figure 5. Results of the analyzed data by using the logistic regressing Equations (3) and (4) for extracting the 90% threshold for the resolution in px/° with the corresponding probability of satisfaction in the DDS. (**a**) Detailed illustration of the logistic regression of the symbol-based projection in the DDS, including the raw data, which is marked with "X" for 1 m data, with circles for 3 m data and triangles for 5 m data; (**b**) Detailed logistic regression of the text-based projection in the DDS including the raw data which is marked with X for 1 m data, with circles for 3 m data and triangles for 5 m data.

In the following section, the consideration of the dependency analysis is coupled with the effective resolution on the ground to deduce resolution requirements for near-field projections in the automotive sector.

4. Discussion

This work's analysis considers the dependencies of the observer's viewing distance, different ambient lighting scenarios and various projection content. All discussed resolution levels are the 90% values of the logistic regression function. This quality threshold level is selected to guarantee a high-quality resolution requirement and consider the worst-case scenario, since the executed studies had a fine-grained asphalt surface. However, previous studies examined resolution requirements for displays or projection screens in cinemas, which have a projection surface with nearly ideal characteristics without a tilted view. However, none derives the necessary characteristics from the customer- or pedestrian-orientated perspective, i.e., the perspective of the receivers of near-field projections in future mobility.

The results of symbol- and text-based projections in PGS and DDS are lower than the resolution of the gap size between the two lines of 85.73 px/° for PGS and 52.93 px/° for DDS in the pre-study. In conclusion, the difference between the results in Table 2 and the pre-study, which defines the maximum perceived resolution on the projection surface, ensures that the tested quality levels were resolvable at the closest observation distance of 1 m. Furthermore, this guarantees that the resulting resolution of symbol- and text-based projections regarding the evaluation aspect of quality has other requirements than the resolvable detail, which is less complex and relates to the static visual acuity task [36].

Therefore, the analyses conducted in this work define some dependencies and simplifications for perceived resolution requirements. First, the impact of ambient lighting is significant (Table 1) for all combinations and defines an explicit dependency in the participants' perception. This significant difference is due to the interaction of rods and cones in the mesopic range of adaptation luminance, which is linked to the increasing acuity at increasing luminance levels [38]. Hence, this phenomenon confirms the use case

of near-field projections for text- and symbol-based projection content in DDS (~6 cd/m^2) or PGS (~1 cd/m^2) due to Valberg's definition [36] of maximal acuity above 2 cd/m^2.

Second, the impact of the projection content focuses on the effective resolution in Table 2 to increase the importance of the resolution values and not just to focus on significance levels [44]. Table 2 also displays the spread of the results with 95% confidence intervals, which deliver an overlay of the symbol- and text-based projection content in the PGS and DDS. The overlay leads to a tendency of a uniform projection system for both projection content varieties regarding the perceived resolution.

5. Conclusions and Outlook

In conclusion, near-field projections have higher visual acuity requirements for text-based projections compared with symbol-based content. The theory especially states that textual acuity tests demand higher visual acuity than sign-based optotype tests due to the more significant cognitive load of the participant [36]. The resolution requirements for near-field projections disagree with the theory of visual acuity regarding the text- or symbol-based content in DDS for 3 m and 5 m viewing distances. External factors such as variation in the roughness of the street surface or the reflection characteristics of the asphalt due to the various viewing distances and viewing angles may be specific to the automotive sector compared to other applications.

Nevertheless, taking the 95% confidence intervals into account, it is possible to find in most combinations an overlap of perceived resolutions in Table 2, which are valid for both projection contents, such as PGS 3 m and DDS 3 m and 5 m. This overlay and the possibility to simplify allows us to focus on safety-relevant situations in future mobility-viewing distances above 1 m. The 3 m and 5 m observation distances will be a widespread use case for safety-relevant projections. A vulnerable road user, such as a pedestrian or cyclist, has to be warned by a safety-relevant projection in hers/his field of view and still has enough time and distance to the vehicle to interact with the symbol- or text-based message to avoid any fatalities. The importance of these use cases is likewise emphasized by the report of DEKRA, which states a cycling braking distance of about 4 m to 5 m depending on the braking system and if the road is wet or dry [45].

To create a realistic setting and thus ensure external validity, we instructed the participants to evaluate the perceived quality of the projection instead of solely focusing on the resolution. Moreover, we used automotive-specific symbols and texts instead of symbols typically used in acuity testing, e.g., Landolt rings. The results in Table 2 are indicators for high-quality resolutions for near-field projections and should be considered in the design of near-field projectors. Future studies should investigate if those indicators apply in different contexts, too. However, these findings are the first indicators in the introduced field of research, which can motivate other researchers focusing on future mobility solutions to concentrate on this application field. Especially other research facilities can confirm the discovered relations and increase the importance of this benchmark.

A generalization of the study results on every text- or symbol-based projection must be carefully examined. Especially for safety-relevant projection content in an urban environment, further research is needed. The static laboratory setting in this work did not include the movements of either the participant or the vehicle, which derogates the conditions of a realistic urban setting. Next, the theoretical derivation based on the subject study should lead to a verification study, where the displayed study aperture evaluates the resulting resolution requirements in a field test and the requirements for the optical system of the near-field projector. Furthermore, the effect of age or sex, which are possible impact factors for visual acuity, is neglected in this work to establish general resolution requirements. Further, the influence of the font style or complexity of characters [46], which is a stylistic characteristic and language dependent, must be considered when focusing on text-based projection content, such as text-based information of the highly automated vehicle or welcoming messages.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed to support the findings of the present study are included in this article. The raw data can be obtained from the authors, upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.
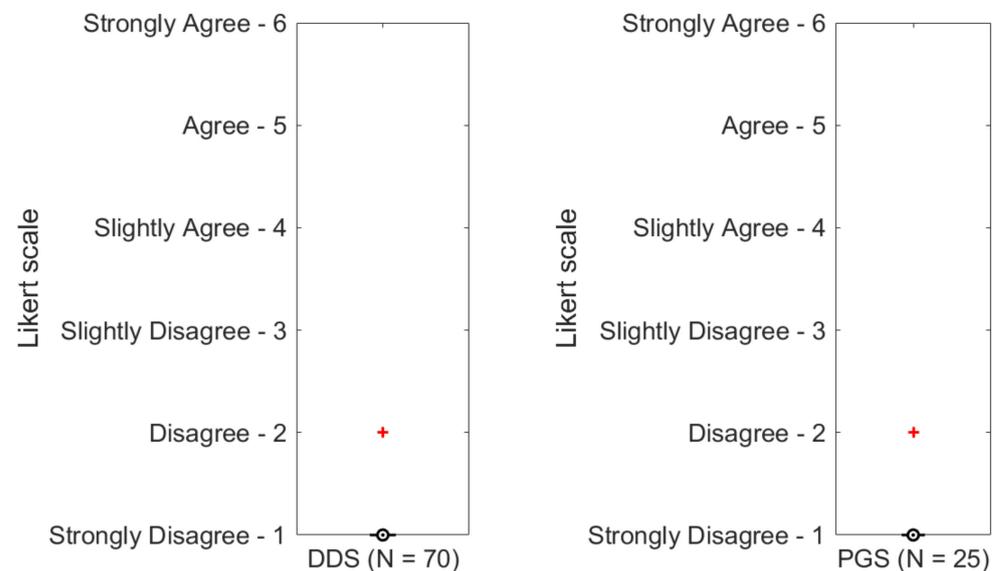
Appendix A

Figure A1. Results of the question, if the participants perceived any glare during the field test with an evaluation of a 6-point Likert scale, where one corresponds to a strong disagreement of the question and 6 a strong agreement. The left boxplot displays the results for the DDS participants and the right boxplot for the PGS participants. The bullet point indicates the median and the red crosses are the outliers. This question was asked to the participants after the study took place.

References

1. Bremer, C.; Noell, W.; Quaranta, G.; Völkel, R. Demanding requirements for interior projection met by micro-optical solutions. In Proceedings of the 14th International Symposium on Automotive Lighting, Darmstadt, Germany, 4–6 April 2022; pp. 646–656.
2. Knöchelmann, M.; Held, M.P.; Kloppenburg, G.; Lachmayer, R. High-resolution headlamps—Technology analysis and system design. *Adv. Opt. Technol.* **2019**, *8*, 33–46. [CrossRef]
3. Moisel, J. Requirements for Future High Resolution Adb Modules. In Proceedings of the 11th International Symposium on Automotive Lighting, Darmstadt, Germany, 28–30 September 2015; pp. 161–169.
4. Namyslo, S.; Courcier, M.; Moisy, E. 360° Near Field Projection—Enhanced safety or just a nice gadget? In Proceedings of the 14th International Symposium on Automotive Lighting, Darmstadt, Germany, 4–6 April 2022; pp. 511–520.
5. Pulliam, J. Investigating Symbol Recognition Time as a Function of System Resolution. In Proceedings of the 14th International Symposium on Automotive Lighting, Darmstadt, Germany, 4–6 April 2022; pp. 162–171.
6. Pulliam, J.; Dabral, S. Innovative Application of Phase Light Modulation for Energy Efficient Projection in Automotive Use-Cases. In Proceedings of the 14th International Symposium on Automotive Lighting, Darmstadt, Germany, 4–6 April 2022; pp. 709–718.
7. Rizvi, S.; Knöchelmann, M.; Ley, P.-P.; Lachmayer, R. Survey of on-road image projection with pixel light systems. In *Photonics, Devices, and Systems VII*; Fliegel, K., Páta, P., Eds.; 2017; Volume 10603, p. 1060314. [CrossRef]

8. Schlöder, U. Dynamic Ground Projections around the Car: The Headlamp as Integrator. In Proceedings of the 14th International Symposium on Automotive Lighting, Darmstadt, Germany, 4–6 April 2022; pp. 538–547.

9. Seiser, B. Dynamic Ground Projection Using DLP®Technology for Automotive Exterior Lighting. 2020. Available online: https://www.ti.com/lit/wp/slyy187/slyy187.pdf?ts=1657029920770&ref_url=https%253A%252F%252Fwww.google.com%252F (accessed on 22 June 2020).

10. Stuckert, A.; Singer, T.; Khanh, T.Q. Analysis and definition of resolution requirements for projections in the near field of a vehicle. In Proceedings of the 14th International Symposium on Automotive Lighting, Darmstadt, Germany, 4–6 April 2022; pp. 521–530.

11. Suwa, M.; Nishimura, M.; Sakata, R. LED Projection Module Enables a Vehicle to Communicate with Pedestrians and Other Vehicles. In Proceedings of the IEEE International Conference on Consumer Electronics (ICCE), Taipei, Taiwan, 12–14 June 2017. [CrossRef]

12. Viršek, M. Automotive car-body lighting digital projector based on LCoS technology. In Proceedings of the 14th International Symposium on Automotive Lighting, Darmstadt, Germany, 4–6 April 2022; pp. 222–232.

13. Brennesholtz, M.S.; Stupp, E.H. *Projection Displays*; Lowe, A.C., Kriss, M.A., Eds.; John and Wiley and Sons: Hoboken, NJ, USA, 2008.

14. Chuang, F. Projection displays—LCD/MEMS/LCoS based. In *Encyclopedia of Modern Optics*; Guenther, B., Steel, D., Eds.; Elsevier Ltd.: Amsterdam, The Netherlands, 2018; Volume 1–5. [CrossRef]

15. Sun, W.-S.; Tien, C.-L.; Ma, C.-H.; Pan, J.-W. Compact LED projector design with high uniformity and efficiency. *Appl. Opt.* **2014**, *53*, H227. [CrossRef] [PubMed]

16. Ackermann, C.; Beggiato, M.; Schubert, S.; Krems, J.F. An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Appl. Ergon.* **2019**, *75*, 272–282. [CrossRef] [PubMed]

17. Dietrich, A.; Willrodt, J.-H.; Wagner, K.; Bengler, K. Projection-based external human-machine interfaces—Enabling interaction between automated vehicles and pedestrian. In Proceedings of the Driving Simulation Conference Europe, Antibes, France, 5–7 September 2018; pp. 43–50.

18. Nguyen, T.T.; Holländer, K.; Hoggenmueller, M.; Parker, C.; Tomitsch, M. Designing for Projection-based Communication between Autonomous Vehicles and Pedestrians. In Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Utrecht, The Netherlands, 21–25 September 2019. [CrossRef]

19. Shibata, Y. Requirement Performance of Road Projection Lamp in Conjuction with Turn Signal Lamp. In Proceedings of the 13th International Symposium on Automative Lighting (ISAL), Darmstadt, Germany, 23–25 September 2019; pp. 362–373.

20. Bleecker, M.L.; Bolla-Wilson, K.; Agnew, J.; Meyers, D.A. Simple visual reaction time: Sex and age differences. *Dev. Neuropsychol.* **1987**, *3*, 165–172. [CrossRef]

21. Gittings, N.S.; Fozard, J.L. Age related changes in visual acuity. *Exp. Gerontol.* **1986**, *21*, 423–433. [CrossRef] [PubMed]

22. McKendrick, A.M.; Chan, Y.M.; Nguyen, B.N. Spatial vision in older adults: Perceptual changes and neural bases. *Ophthalmic Physiol. Opt.* **2018**, *38*, 363–375. [CrossRef] [PubMed]

23. Sivak, M.; Schoettle, B. Recent Changes in the Age Composition of Drivers in 15 Countries. *Traffic Inj. Prev.* **2012**, *13*, 126–132. [CrossRef] [PubMed]

24. Barten, P.G.J. The effects of picture size and definition on perceived image quality. *IEEE Trans. Electron Devices* **1989**, *36*, 1865–1869. [CrossRef]

25. Heron, G.; Furby, H.P.; Walker, R.J.; Lane, C.S.; Judge, O.J.E. Relationship between visual acuity and observation distance. *Ophthalmic Physiol. Opt.* **1995**, *15*, 23–30. [CrossRef] [PubMed]

26. Jesty, L.C. The relation between picture size, viewing distance and picture quality. *Proc. IEE Part B Radio Electron. Eng.* **1958**, *105*, 425–439. [CrossRef]

27. Lund, A.M. Influence of Video Image Size and Resolution on Viewing-Distance Preferences. *SMPTE J.* **1993**, *102*, 406–415. [CrossRef]

28. Shlaer, S. The Relation between Visual Acuity and Illumination. *J. Gen. Physiol.* **1937**, *11*, 255–281. [CrossRef] [PubMed]

29. *DIN 1450:2013-04*; Lettering—Legibility. Beuth-Verlag: Berlin, Germany, 2013.

30. *DIN ISO 3864-1:2012-06*; Graphical Symbols—Safety Colours and Safety Signs—Part 1: Design Principles for Safety Signs and Safety Markings. ISO: Geneva, Switzerland, 2012. [CrossRef]

31. *DIN EN 12464-2:2014-05, 20*; Light and Lighting—Lighting of Work Places—Part 2: Outdoor Work Places. Beuth-Verlag: Berlin, Germany, 2014.

32. MAXWELL. MP-WU5603 Laser Projector. 2022. Available online: https://maxellproav.com/product/mp-wu5603-laser-projector/ (accessed on 7 October 2020).

33. Kingdom, F.A.A.; Prins, N. Psychophysics: A Practical Introduction: Second Edition. In *Psychophysics: A Practical Introduction*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2016. [CrossRef]

34. Statistisches Bundesamt. Mikrozensus—Fragen zur Gesundheit—Körpermaße der Bevölkerung 2017. 2018. Available online: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Gesundheit/Gesundheitszustand-Relevantes-Verhalten/Publikationen/Downloads-Gesundheitszustand/koerpermasse-5239003179004.html (accessed on 27 August 2020).

35. *CIE 144:2001*; Road Surface and Road Marking Reflection Characteristics, Commission Internationale de L'eclairage, Technical Report, Vienna. Beuth-Verlag: Berlin, Germany, 2001.

36.   Valberg, A. *Light Vision Color*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2005.

37.   Cogent. Cogent 2000 (1.33). The Wellcome Department of Imaging Neuroscience. 2020. Available online: http://www.vislab.ucl. ac.uk/cogent_2000.php (accessed on 9 November 2020).

38.   Hauske, G. *Systemtheorie der Visuellen Wahrnehmung*; Teubner, B.G., Ed.; Springer: Berlin/Heidelberg, Germany, 2003.

39.   Linschoten, M.R.; Harvey, L.O.; Eller, P.M.; Jafek, B.W. Fast and accurate measurement of taste and smell thresholds using a maximum-likelihood adaptive staircase procedure. *Percept. Psychophys.* **2001**, *63*, 1330–1347. [CrossRef] [PubMed]

40.   Macmillan, N.A.; Creelman, C.D. *Detection Theory: A User's Guide*, 2nd ed.; Psychology Press: London, UK, 2004. [CrossRef]

41.   Harvey, L.O. Efficient estimation of sensroy thresholds with ML-PEST. *Spat. Vis.* **1997**, *11*, 121–128. [CrossRef] [PubMed]

42.   Field, A.; Miles, J.; Field, Z. Discovering statistics using R. In *Choice Reviews Online*; SAGE: Thousand Oaks, CA, USA, 2012; Volume 50.

43.   Ellis, P.D. *The Essential Guide to Effect Sizes: Statistical Power, Meta-Analysis, and the Interpretation of Research Results*, 1st ed.; Cambridge University Press: Cambridge, UK, 2010. [CrossRef]

44.   Amrhein, V.; Greenland, S.; McShane, B. Scientists rise up against statistical significance. *Nature* **2019**, *567*, 305–307. [CrossRef] [PubMed]

45.   Gaul, M. Bicycle: It Depends on the Braking Power. DEKRA Solutions. 2020. Available online: https://www.dekra-solutions. com/2020/12/bicycle-it-depends-on-the-braking-power/?lang=en (accessed on 28 December 2022).

46.   Wang, C.-X.; Lin, N.; Guo, Y.-X. Visual requirement for Chinese reading with normal vision. *Brain Behav.* **2019**, *9*, e01216. [CrossRef] [PubMed]