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ILLUMINATION REQUIREMENTS FOR GAZE PERCEPTION

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Abstract

Road lighting in residential and mixed-traffic areas should provide a feeling of safety to pedestrians. Among the critical visual tasks that support judgement of intentions, perception of gaze direction has been found to be the most difficult. Question now is which road lighting conditions are needed to enable a good-enough perception of another's' gaze direction. This study describes an experiment which collected perceived gaze directions for 30 participants under 5 levels of vertical illuminance and 3 levels of horizontal illuminance. Gaze perception was shown to be highly significantly dependent on vertical illuminance level, but not on horizontal illuminance, or observer age. Based on the findings, for road lighting in residential areas, a minimum vertical illuminance level of 3.6 lux is recommended, independent of the required horizontal illuminance level.

Keywords: Road lighting, Pedestrians, Vertical illumination, Gaze direction

1 Introduction

Most of the research that explored the effect of lighting conditions on one's ability to judge another person use either facial recognition or identification as measures for the quality of perception of facial features (e.g. Boyce, 1990; Fujiyama, 2005; Raynham, 2003). Indeed, the current recommendations for road lighting in residential areas are based on the necessity for a pedestrian to recognize another's face (CIE, 2010). However, the ability to recognize another person on the street at night alone cannot be considered adequate for judging the intentions of others. To assess possible threats, also the emotion and focus of attention are important and the latter can be deduced from gaze direction (Fotios, 2015). Not only is gaze direction an important cue for where another person is directing his or her attention (Langton, 2000), also it informs us about his or her walking direction (Nummenmaa, 2009).

Whereas perception of gaze direction has been found to be the most difficult among the critical visual tasks (Donners, 2017; Fotios, 2015), it could be considered the cornerstone when designing road lighting for perceived safety. With lighting conditions that allow for a confident perception of gaze direction, identification and facial recognition can be assumed sufficient. Accordingly, to design road lighting in residential areas for enhancement of the pedestrians' perceived safety at night time, a thorough understanding is required about how road lighting conditions affect perception of gaze direction. Therefore, the current research aims to gain deeper insight in the effects of different lighting conditions on one's ability to perceive gaze direction.

Some earlier research examined the effect of lighting conditions on the ability of people to perceive another's gaze direction (Donners, 2017; Fotios, 2015). The ability to perceive gaze direction in both studies was determined by employment of a forced-choice judgement method in which participants either choose whether the gaze direction is toward or averted from them (Fotios, 2015) or whether gaze direction is at the left, at the right or toward the participant (Donners, 2017). Thereby, the findings of the mentioned research are restricted to knowledge about the probability of correct estimation of gaze direction under specific lighting conditions. The current study aims to gain further knowledge on this topic by answering the question how one's ability to perceive another's gaze direction depends on road lighting conditions, specifically the vertical illuminance on the face and the horizontal illuminance on the road surface.

To enable face perception, current lighting recommendations, such as CIE (2010) or the derived EN 13201:2014, provide additional requirements for minimal vertical illuminance levels in pedestrian and low speed traffic areas "if facial recognition is necessary", with the required minimal vertical illuminance in a range of 0.6 lux to 5 lux, increasing with the average horizontal illuminance level. Although it sounds logical that the required illumination on the face would depend on the background light level, determining the adaptation state of the observer, there is no known experimental evidence for the chosen levels of vertical illumination nor for their relation to the horizontal illuminance.

A practical aspect is the interpersonal distance at which a pedestrian requires to be able to judge another's intentions. Using eye-tracking devices, Fotios (2015) investigated the typical interpersonal distances and the typical duration of continuous fixation when looking at other pedestrians at night time. Their results suggest that interpersonal judgements are made at a distance of 15 m in fixations with an average duration of 480 ms.

An established method from psychology looking into gaze perception (Anstis, 1969) will be used. Studying gaze perception in human-human and human-robot interaction (e.g. Hakala, 2016; Masame, 1990; West, 2013). Cuijpers (2010), it measures the accuracy of gaze direction perception. Here it is applied under various lighting conditions typical for road lighting, thereby contributing to the improvement of road lighting recommendations for pedestrians. Three hypotheses will be tested. First, we assume that gaze accuracy increases with increasing vertical illumination. Secondly, that at higher vertical to background illuminance ratio leads to a higher accuracy and finally that accuracy will be lower for a 55+ age group, compared to a -35 age group.

2 Methods

A total of 32 naïve participants with normal eyesight took part in the experiment. Two participants did not finish the experiment because of insufficient eyesight to perform the experimental task. Data of these two were excluded from analysis. Participants were selected with an age either between 20 and 35 or above 55 years old. Of the remaining 30 participants, each age group consisted of 15 participants.

The experiment used a mixed design, including two within-subject factors, vertical illuminance and horizontal illuminance, and one between-subject factor, age. Each participant judged a real person's gaze directions under 15 combinations of vertical illuminance (5 levels) and horizontal illuminance (3 levels). In each of the 15 combinations of lighting conditions, a participant judged 5 gaze directions, which were all presented twice for every combination of vertical and horizontal illuminance. The sequence in which the levels of vertical illuminance, the levels of horizontal illuminance and gaze directions were presented were all completely randomized for each participant.

Gaze directions were presented by the experimenter, a 24-year-old Caucasian male with brown hair and blue eyes. At 122.5 cm in front of the looker, a horizontal scale was suspended at 6 cm above eye level. The scale was marked with five target points, indicating the five different gaze directions. The lateral positions of the target points, referred to as gaze locations, were located at respectively -43.5 cm, -21.75 cm, 0 cm, 21.75 cm and 43.5 cm, relative to the center of the scale. Figure 3.1 shows a schematic representation of the five target points and the corresponding gaze directions. Negative gaze locations thus represented gaze directions to the left, whereas positive gaze locations represent gaze directions to the right. The target point located at 0 cm represented a straightforward gaze. The five gaze directions corresponded to gaze angles of -19.6°, -10°, 0°, 10° and 19.6° relative to a looker's direct gaze.

The experiment took place in a blacked-out hallway with dimensions of 21 by 1.9 m. Both the looker and the participant were seated on adjustable office chairs and faced each other directly at a distance of 12.5 m. Head displacements were minimized by using chinrests. The table in front of the participant supported a laser pointer, to indicate perceived gaze locations. A horizontal scale was suspended in front of the looker, above eye level (Figure 2).

Vertical illumination in the experimental setup was simulated through illumination of the looker's face. Horizontal illumination, however, was simulated through illumination of the background

behind the looker seen from the participant's perspective. From now on, the two different sources of illumination will therefore be referred to 'face illumination' and 'background illumination'. The different levels illumination of the looker's face were realized by a dimmable LED spot (Philips StyliD Compact Power, 4000 K, Ra>80). The spot was suspended from the ceiling on a longitudinal distance of 2.9 m from the looker, so that light reached the looker's



Figure 1 – Schematic representations of the top and side view of the experimental setup, including relevant dimensions. 'L' refers to the looker and 'P' refers to the participant.

face at an angle of 44° relative to the horizontal. The system was set up so that an illuminance level of 0.5, 1.25, 2.5, 5 or 10 lux was achieved on the position of the looker's face.

The background was illuminated with a ceiling luminaire (Philips Savio LED luminaire (4000 K, Ra>80), installed in the ceiling 4 m behind the experimenter. The back and side walls and the ceiling were white. The luminance of the background was set to the values produced by the horizontal illumination ($E_{h,av}$) on a road surface, chosen according to lighting classes P1, P3 and P5 (CIE, 2010), corresponding to illuminance levels of respectively 3.0, 7.5 and 15 lux. In order to reproduce the amount of light reflected from the street surface at night, typical values of background luminance corresponding to these three lighting classes were calculated to be 0.3, 0.8 and 1.5 cd/m2. These settings were checked using a luminance camera (LMK5, Technoteam).

By rotating a 1mW laser pointer horizontally in its holder, the participant indicated his or her perceived gaze location with the projected laser dot on the scale. Opal glass was used as material for the scale so that the projected laser dot also could be seen from the side of the looker. In addition to the earlier mentioned target points, the scale was marked with a continuous scale at the side of the looker. This continuous scale was used by the looker to read a participant's response. Both the target points and the continuous scale were realized using glow-in-the-dark tape, so that they could be sufficiently seen in the dim lighting conditions that were used. Due to dimensions of the experimental room, the maximal width of the scale was 1.4 m. The continuous scale therefore ranged from -70 cm to 70 cm, with 0 cm in the exact line of sight of the looker.

The positions of the extreme target points (-43.5 and 43.5 cm) were based on an expected maximum overestimation of gaze angle of \pm 70%. This maximal percentage of overestimation was based on results of research by Anstis et al. (1969). A 70% overestimation of gaze angle when the looker gazes at the extreme left target point (-43.5 cm) or the extreme right target point (43.5 cm) would thus lead to a perceived gaze location at the limit of either side of the

scale. Figure 3.3 shows a schematic representation of the scale with the continuous scale, the five target points for the looker and an exemplar location of the projected laser dot representing a participant's response.

After giving informed consent, the participant was tested on his/her visual acuity, using a Landolt C chart. In the subsequent explanation of the experimental procedure, it was stressed to the participant that trials in which the looker's gaze direction could not be seen (well), still required a 'best guess' answer. The reason for this was twofold. Firstly, research on perception shows that subjects commonly can perform a visual task better than they think themselves. Secondly, a missing answer would be at the expense of the data collection. After explanation of the experimental procedure, the looker took place in his chair and performed a set of random gaze directions to check whether the participant could sufficiently see the looker's pupils under the office lighting conditions, considering the large interpersonal distance used. When this was the case, all lights were turned off and an experimental demo was started. Besides making the participant acquainted with the experimental procedure and task, the demo served the goal to make participants adapt to the dim light conditions. The demo contained 15 random combinations of levels of face illuminance, levels of background luminance and gaze directions and took approximately 3 minutes. After the demo was finished and all remaining questions of participant were answered, the real experiment was started.



Figure 2 – Schematic representation of the scale as seen from the looker's side. Red markings on the bottom of the scale indicate the five target points. The red dot on top of the scale represents an indication of a perceived gaze location, in this example equal to -31 cm.

After the background luminaire had been on for 3 seconds, the looker's face was illuminated. Based on research of Fotios et al. (2015), initially an illumination time of 500 ms was used. During pilot experiments, however, was found that this was too little time for the participant to be able to focus on the looker's face. Therefore, the looker's face was illuminated by the spot for a duration of 1 second.

As indicator for the participant that the looker's face is about to be illuminated, a short 'beep' sounded through a set of speakers 1 second before the face illumination switched on. In Figure 3.4 this is indicated by a speaker logo. During the 3 seconds before the looker's face was illuminated, the target point for that specific trial was displayed on the laptop. During illumination of his face, the looker gazed at the specific target point, at the actual gaze location *X*, with corresponding actual gaze angle χ .

After the face illumination switched off, the participant indicated the perceived gaze location Y by aiming the laser pointer at the location on the scale where (s)he believed the looker was looking. The participant could use as much time as (s)he needed for indicating the perceived gaze location for each trial. After Y was recorded for this trial, the next trial automatically started.

For each participant 10 perceived gaze locations Y were recorded under 15 different combinations of face and background luminance levels. This resulted in 150 data points for each participant, or a total of 4500 data points for 30 participants. To assess the accuracy of gaze perception, gaze error ε was calculated: $\varepsilon = Y - X$. Gaze error ε contains information of both the magnitude and the direction of the error. These linear fits can be written as $\varepsilon = A^*X + B$, with A representing the slope of the linear fit and B representing the intercept of the linear fit. Subsequently, it is tested whether both slope A and intercept B are significantly affected by the experimental conditions. In this way the main hypotheses are tested, using ANOVA tests using StatalC 14 (StataCorp, 2015).

3 Results

For each of the 30 participants, 150 responses were recorded. This resulted in a total of 4500 observations. Due to a software issue, 14 responses were lost for a single participant. Furthermore, 3 observations were deleted because of errors during input. Therefore, a total of 4483 observations were usable for statistical analysis.



Figure 3 – Mean values of intercept B ± SE as function of face illuminance level

Table 1 – Results of ANOVA with slope A as dependent variable, face illuminance level, background luminance level and age as independent variables (N=450). H-F refers to Huynh-Feldt corrected p-values, G-G refers to Greenhouse-Geisser corrected p-values.

		р		
df	F	Regular	H-F	G-G
4	170.54	0.000**	0.000**	0.000**
2	0.55	0.5823	0.5823	0.5765
1	0.12	0.7285	-	-
8	0.60	0.7735	0.7520	0.7078
	df 4 2 1 8	df F 4 170.54 2 0.55 1 0.12 8 0.60	p p df F Regular 4 170.54 0.000** 2 0.55 0.5823 1 0.12 0.7285 8 0.60 0.7735	p df F Regular H-F 4 170.54 0.000** 0.000** 2 0.55 0.5823 0.5823 1 0.12 0.7285 - 8 0.60 0.7735 0.7520

Figure 3 shows how the relationship between X and ε is affected by lighting conditions for the entire sample size. Gaze errors appear to be generally positive for negative gaze locations and generally negative for positive gaze locations for the lower levels of face illuminance. For higher levels of face illuminance on the other hand, gaze errors are generally negative for negative gaze locations, while positive for positive gaze location. Additionally, gaze errors are found to be generally larger for larger values of gaze location X.

Since the independent variables used in the experiment are all categorical, the predicted effects of level of vertical illuminance (H₁), contrast of vertical to horizontal illuminance (H₂) and age (H₃) on accuracy of gaze perception are modelled using ANOVA. Because of the violation of sphericity, Greenhouse-Geisser (1959) and Huynh-Feldt (1976) corrections are used, changing the number of degrees of freedom, resulting in a decreased Type I error. Face illuminance has a highly significant effect on slope A (p < 0.001). However, both Huynh-Feldt and Greenhouse-Geisser corrected p-values suggest that face illuminance does not significantly influence intercept B (p > 0.05).

In figure 4, the mean of slope A with corresponding standard errors is plotted against the level of face illuminance. The value for slope A starts around -0.8 for a face illuminance level of 0.5 lux and vastly increases for an increasing level of face illuminance level. For a face illuminance level of 2.5 lux the slope is approximately 0, after which it moderately increases further up to about 0.2 for a face illuminance level of 10 lux. Important to note is that for a value for slope A of 0, indicated in the graph with a dashed line, perceived gaze location Y is exactly equal to actual gaze location X for all target positions. The dashed line therefore represents geometrically correct judgements of gaze location.

Using a nonlinear least squares method in MATLAB R2018a, this asymptote in slope A versus vertical illuminance level is approximated with a negative exponential function. A approximates a value of 0.22 for high values of vertical illuminance. This implies that under face illuminance level higher than 10 lux, actual gaze location X is overestimated with an average of 22%.



Figure 4 – Dependence of slope A on the level of vertical illumination on the face of the looker. Line indicates exponential curve fit.

4 Discussion

The first hypothesis states that an increased level of vertical illuminance leads to a more accurate perception of gaze direction. Vertical illuminance is shown to affect the slope A to a highly significant extent, indicating that the proportional deviation of perceived gaze direction varies for different lighting conditions, strongly confirming the first hypothesis.

The second hypothesis said that an increased level of vertical illuminance relative to horizontal illuminance leads to a accurate perception of gaze direction. Both slope A and intercept B were not found be significantly influenced by the background illuminance, or by an interaction between vertical and horizontal illuminance. Both constant deviation and proportional deviation of perceived gaze direction are thus not affected by the contrast of vertical to horizontal illuminance. Therefore, H₂ is rejected.

Hypothesis 3 argued that people aged above 55 perceive gaze direction with a lower accuracy than people aged under 35. No significant effects of age were found on both slope A and intercept B, rejecting this hypothesis.

4.1 Implications of findings

To the authors' best knowledge, this is the first time that the effects of lighting conditions on peoples' accuracy of perceived gaze direction are investigated. Where former research (Fotios et al., 2015; Donners et al., 2017) found differences in a pedestrian's probability of correct identification of gaze direction due to level of illumination, findings of the current study hold a relationship between vertical illuminance level and the extent to which a pedestrian either under- or overestimates a looker's gaze direction.

Donners et al. (2017) also found on a similar interpersonal distance that level of vertical illuminance affects one's ability to perceive gaze direction. The interaction effect of face illuminance and background luminance found by Donners et al. (2017), however, was not found in the current study. Moreover, the effect of age found by Donners et al. (2017) was also not found in the current study.

The relationship between vertical illuminance and accuracy of gaze perception, as shown in figure 3, can also be related back to earlier findings in the field of perception. On the one hand, the looker's eye-position is difficult to perceive under low levels of vertical illuminance, which may therefore lead to the earlier discussed ego-centric bias (Masame, 1990):

Low light levels lead to higher uncertainties in gaze perception and one tends to overestimate the presence of eye-contact. This corresponds to an underestimation of the looker's gaze direction. On the other hand, an overestimation effect occurs for vertical illuminance levels higher than 2.6 lux. This suggests that pedestrians perceive the looker's eye position increasingly better for vertical illuminance levels above 2.6 lux, and thereby increasingly overestimate the corresponding gaze direction due to a perceptual bias (Anstis, 1969).

The current study suggests that pedestrians' overestimation of another's gaze direction saturates to an average of 22% for extreme levels of vertical illuminance (> 10 lux). This is a smaller overestimation than found by Anstis et al. (1969), who found an overestimation of 50%. This difference in findings may originate from different sources. The much larger interpersonal distance and the restricted observation time of the current study in relation to the study of Anstis et al. (1969), both lead to a decreased visibility of the looker's eyes. Thereby, the perceptual bias of the observer, leading to overestimation of gaze direction, may occur to a lower extent in the current study than in the study of Anstis et al. (1969).

4.2 Recommendations for road lighting

Findings of the current study can be used as benchmark for design of road lighting standards for residential areas. While findings of the current study exclusively suggest an eligible effect of vertical illuminance level, recommendations based on these findings restrain to ranges of vertical illuminance. Recommendations can be provided based on two distinct concepts that need explanation: perceptually correct gaze perception and geometrically correct gaze perception. Perceptually correct gaze perception refers to the situation in which gaze perception

is perceived under maximal visibility conditions, whereas geometrically correct gaze perception refers to the situation in which perceived gaze direction is equal to the actual gaze direction along the measured field of gaze.

Figure 4 shows that overestimation of gaze perception saturates for higher values of vertical illuminance, perceptually correct gaze perception is assumed to be an overestimation of 22% under the tested conditions. In order to facilitate this perceptually correct gaze perception, lighting levels would be desired that realize perception of gaze direction that does not significantly differ from this value. The minimum level of vertical illuminance that allows for this is calculated by subtracting the value for perceptually correct gaze perception with the average CI of slope A across the different levels of vertical illuminance. Following this approach, a minimum allowable overestimation equal to 11.2% is found. The level of vertical illuminance that suggest that a person's face should be illuminated with a minimum level of 3.6 lux in order to facilitate perceptually correct gaze perception.

Worthwhile to stress is that gaze direction is more accurately perceived for lower levels of vertical illuminance. Geometrically correct perception of gaze direction was namely found for a vertical illuminance level of 2.6 lux. Aiming to design road lighting that facilitates this correct perception of gaze direction, a vertical illuminance level between 2.0 and 3.6 lux should be effectuated. This minimum and maximum value are again based on the average CI of slope A. Inside this range of vertical illuminance, perception of gaze direction thus does not significantly differ from geometrically correct perception of gaze direction. However, should be noted that designing road lighting for correct perception of gaze direction is at the expense of the level of visibility level of a pedestrian.

With respect to the current recommendations for minimum vertical illuminance in residential areas by CIE (2010,) perceptually correct gaze perception is achieved only in lighting class P1, whereas geometrically correct gaze perception is achieved in lighting class P2 and nearly in lighting class P3. Recommendations for minimum vertical illuminance for lighting classes P4, P5 and P6 are thus too low to allow for either perceptually or geometrically correct gaze perception. More importantly, however, is that the minimum level of vertical illuminance has not been found to depend on the level of background illuminance. This means that the current findings suggest that the linear relationship between horizontal and vertical illuminance as suggested by CIE (2010) does not apply.

4.3 Limitations and recommendations

Of course, this study has a number of limitations. During the design of the experiment, some decisions were made due to practicalities, with some of these at the expense of scientific validity. First of all, Fotios et al. (2015a) reported that a typical observation time for continuous fixation on other pedestrians after dark is 480 ms. This study, however, used twice the duration of this observation time. Assuming that a decrease of observation results in a lower visibility for the observer, it is expected that the found relationship between vertical illuminance level and slope A is shifted somewhat to the right. Therefore, it should be taken into account that the resulting recommendation of 3.6 lux for a minimum vertical illuminance is a slight underestimation.

Furthermore, the time included in the experiment for participants to adapt to the dim lighting conditions was rather assumed than based on a theoretical value. Participants in reality needed longer than 3 minutes to adapt to the dim lighting conditions. By non-full adaptation to the dim lighting conditions for the first number of experimental trials, participants are thus expected to have a decreased visibility. Based on this observation, again a slightly higher recommended minimum level of vertical illuminance should be regarded.

A wider horizontal scale positioned closer to the participant reduces the sensitivity to pointing errors made by the participants. In the current study the relationship between road lighting conditions and accuracy of gaze perception was obtained by measuring perceived gaze directions corresponding to only five actual gaze directions. discusses a trade-off between the so called close-to-face gaze directions and far-to-face (or eccentric) gaze directions. Whereas

This study, apart from a direct gaze direction, incorporated only far-to-face gaze directions (Masame, 1990). It is desired to also investigate close-to-face gaze directions. Lastly, the looker in the experiment was a 24 years old Caucasian man with brown hair and blue eyes. The ability to perceive another's gaze direction may also depend on the looker's facial features, such as the size and colour of the eyes. To get an idea about how these details influence the required lighting conditions, similar experiments should be conducted with lookers that have different facial features. In that way, a standard can be developed for recommendations of lighting conditions that enhance perception of gaze direction.

5 Conclusions

This study investigated the effect of road lighting conditions on the accuracy of perceived gaze direction, obtained by plotting gaze error (perceived gaze location – actual gaze location) against the looker's actual gaze location. The slope of this relationship was found to be highly significantly affected by vertical illuminance. For vertical illuminance levels up to 2.6 lux, gaze direction is decreasingly underestimated. For levels above 2.6 lux gaze direction gaze direction is increasingly overestimated. In order to ensure perception of gaze direction for pedestrians with the same bias as found at high light levels, this study suggests a minimum level of vertical illuminance of 3.6 lux for road lighting for pedestrians. Moreover, the minimum level of vertical illuminance has not been found to depend on the level of horizontal illuminance. The linear relationship between vertical and horizontal illuminance suggested by CIE (2010) is not confirmed by this study. Besides, accuracy of gaze perception has not been found to be affected by age. Two important aspects require further examination. The origin of the intrapersonal variation should be established and similar experiments should be performed using lookers with different facial features. In that way, a standard can be developed for recommendations of lighting conditions that enhance perception of gaze direction.

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