Human Gaze Estimation: Comparing Accuracy in Naturalistic and Quad Brightness Conditions

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Abstract

This paper investigates gaze estimation as a cognitive process and proposes that human gaze estimation can be modelled with an average brightness mechanism, split into four sectors or in other words, a quad brightness mechanism. This mechanism would allow further investigation into the exploration of human gaze and might help untangle different concepts related to gaze estimation and joint attention. The aim of this paper was to confirm whether humans are indeed able to estimate gaze in a quad brightness condition and, secondly, to test their accuracy in such a condition.

For this research, face images were created and manipulated to show four quadrants with average brightness. These images were run through the times 70ms, 140ms, 400ms, 600ms and 1000ms in both original and manipulated form and participants estimated the gaze orientation of each conditions faces.

It was found that participants were able to estimate the gaze orientation of quad brightness images. Their accuracy was, however, somewhat worse with a deviation of 10°. In a larger context and based on the findings, it is likely that the quad brightness process models, either a section of a larger process, of gaze estimations or is part of multiple and separate processes for gaze estimations. Further research could investigate how these processes are linked, as well as the influence of head directions. With these findings, there is a new and promising model that can be used to explain and investigate gaze estimations. If quad brightness is either entirely or partly matching with the actual human process, this could also lead to further applications, both in cognitive psychology for perceptual or attention-focused research and autism research to investigate perceptual differences.

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Introduction

Our gaze is directly connected to our behaviour, as it shapes our perception of the world, but is also used for non-verbal communication and cooperation via shared gaze. Gaze can be defined as "to look at something or someone for a long time, especially in surprise or admiration, or because you are thinking about something else" (Cambridge University Press, n.d.). From this, three important aspects of gaze can be identified. First, gaze is a form of looking, and as such, a behaviour. Second, it has a component of time. Third, and most importantly, gaze is often an attentive behaviour and as such a cognitive process. Furthermore, shared gaze or joint attention adds more complexity to gaze by adding both cooperation and the process of simultaneous attention to an object in a social situation.

Additionally, gaze was shown to influence human emotions. One example is the study from Adams Jr and Kleck (2005), which showed that the gaze orientation, e.g. direct vs averted gaze, has an enhancing influence on particular emotions, such as an increase of joy in the direct gaze condition or an increase of sadness in the averted gaze condition. This directly shows the impact of gaze in social interactions on the emotions humans experience. Furthermore, in their research article, Rigato and Farroni (2013) also wrote on the effects of gaze and emotions in a spatial cueing setting. They reported multiple studies which investigated the reaction time in a detection task in relation to gaze and emotion. While the results were mixed, there is an indication that facial expressions, in their case fearful expressions, lead to a faster shift in attention towards a cued target.

Overall, this gives a glimpse of the impact of gaze on our emotions and possibly behaviour. Building on this background, the next section of the introduction focuses on the question of why the human eye and gaze function in their current form.

Evolutionary Background

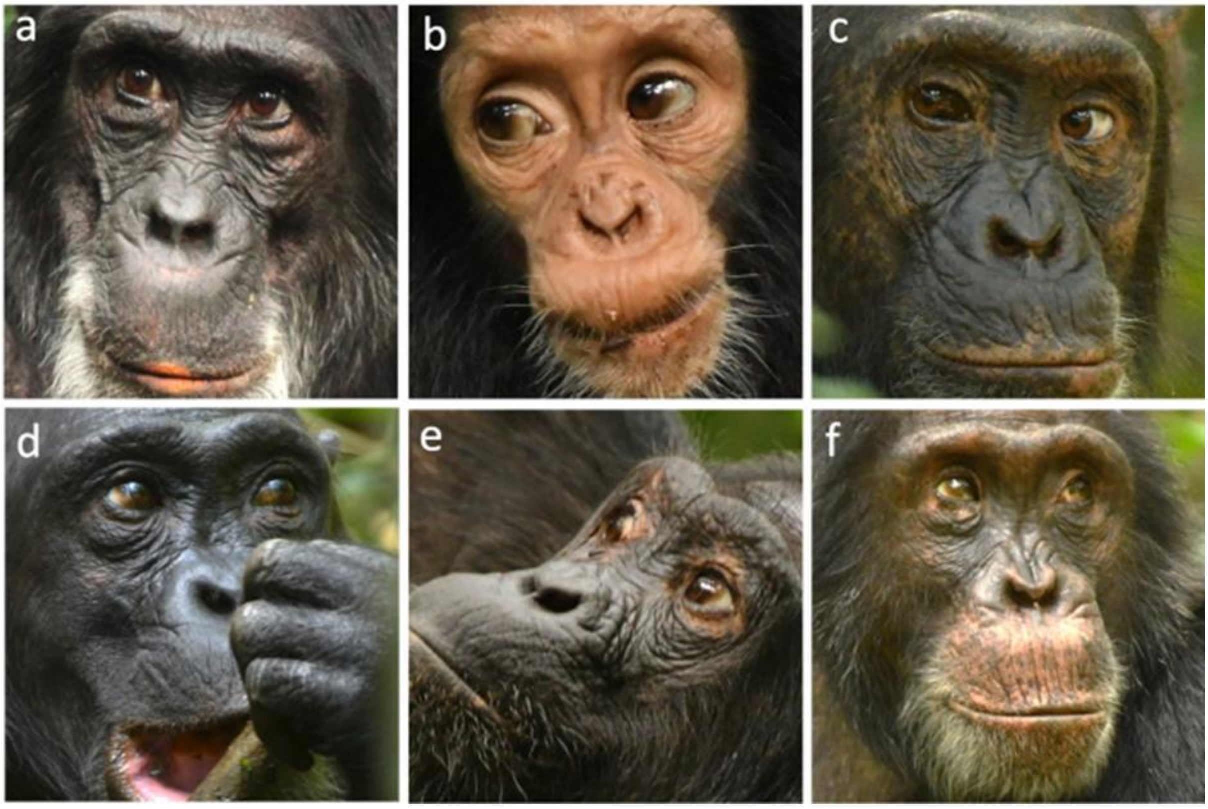
One perspective to investigate this is an evolutionary approach. Most notably, the cooperative eye hypothesis proposes that "the visual appearance of the human eyeball evolved specifically to facilitate reading the glance direction." (Schmettow, 2025). Building on the cooperative eye hypothesis, Tomasello et al. (2007) investigated the differences in gaze following between human infants and great apes. In their study, they controlled for head movements vs eye movements and found an important difference. For great apes, the main factor in gaze following was head direction, with the great apes following the direction of the heads in the highest number of cases. Notably, they also followed head movements when eyes were closed, or they saw the heads from behind. For human infants, the eyes were the main factor in gaze following. As such, gaze seems to be more eye-based in humans than in primates. These findings support the cooperative eye movements hypothesis and would indicate that throughout human evolution, eye-based gaze orientation offered some specific advantage.

Furthermore, in the initial paper describing the cooperative eye hypothesis, by Kobayashi and Kohshima (2001), some unique properties of the human eyes are stated. The human eye has a white sclera with no pigmentation, this sclera is exceptionally visible compared to other primates and the human eyes are stretched horizontally to a high degree. Notably, the pigmented eyes of other primates might be an adaptation to camouflage their gaze orientation, while the white sclera of the human eyes is an adaptation to do the opposite, increasing the visibility of gaze orientation (Kobayashi & Kohshima, 2001).

However, one new study from Clark et al. (2023) did find white sclera in other primate species when looking at wildlife pictures and primates from zoos, under certain conditions (see Figure 1). The primates with white sclera were mainly younger primates, and the sclera were most visible when they averted their gaze. One possible explanation of this might be a common ancestor with humans. If further reports of such very limited and conditional white sclera are reproduced, it would, however, ironically, further cement the cooperative eye hypothesis. Given that the most likely result of humans having a white sclera and some primates having partly white sclera is that there is a common ancestry, the direct question would be why only humans have a full white sclera. With the most plausible and simplest potential answer being the cooperative eye hypothesis itself. Suggesting that due to a theoretical different need for cooperation and shared gaze, the white sclera evolved differently in humans.

Figure 1

Example of white Sclera



Note. This is a cropped version of the original image from Clark et al., containing only the images with white sclera. Permission to use these images was granted.

Gaze Precision

Going further from this, it can be of interest to delve deeper into how the human gaze process works. Again, keeping the white sclera of the human eye in mind, the ability to detect brightness and light differences should be investigated. Frank Keil (2014) reported in his book that the typical human eye is able to differentiate up to a 1% difference on a light scale. Furthermore, he states that the differentiation of brightness happens in the *early* levels of processing at the retina in the back of the eye (Keil, 2014). This would suggest the possibility of an automated process that requires little mental awareness.

Furthermore, in a study by Bock et al. (2008), the precision of gaze following was measured. This was done in multiple conditions with two participants facing each other. Between the participants, an object was shown in a circular setup, with one participant gazing at the object and the second participant estimating the gaze orientation. They reported a pooled global accuracy of 3.17° and an example of a local mean accuracy ranges are 3.2° horizontally and 2.9° vertically. As such, the human eye shows remarkable precision in both gaze following and differentiation of brightness.

Early Development of Gaze

Adding onto this, the development of babies can help us identify when the gaze process is developed. Regarding face perception, specifically Keil (2014) notes a two-system process of face recognition. The first system is activated mainly when it recognises moving face shapes and seems to be innate. However, it is a rudimentary system only capable of supporting the most basic recognition of face-like stimuli. The second system is more sophisticated and is able to recognise detailed faces and patterns, but requires information from the first system to develop itself over time, only being functional around the age of 6 months. The second system then becomes the main mechanism for face recognition. Since the recognition of faces is similar to and/or connected with the recognition of eyes and gaze, there may be a corresponding link or similarities in the developmental processes of gaze recognition. If two separate systems are involved, they might converge during development to form a single functional system, or alternatively, multiple systems may persist to support different aspects of the same process.

Furthermore, the development of gaze recognition also seems to happen in two separate stages according to Silverstein (2021), with gaze recognition first being learning on the horizontal plane and later on the vertical plane. In infants, there were no notable differences in latency for horizontal and vertical conditions at the age of 6 months, however at the age of 12 months, infants were notably better in the horizontal condition. Thus, there seems to be at least an indication that the systems of gaze recognition are developed around the time of 6 months to 12 months. Furthermore, the findings of Brooks and Meltzoff (2005) indicate that infants aged 9 months followed both heads with closed eyes and heads with open eyes, whereas infants aged 10 months and older only followed head movements with open eyes.

These findings give two important implications. First, evidence suggests that face and gaze recognition may rely on separate learning systems. Moreover, face recognition appears to involve multiple systems, but it remains uncertain whether gaze recognition follows a similar pattern. Therefore, it should not be ruled out that there are multiple systems later on in life that operate together. Second, the recognition of gazes and eyes seems to emerge around the age of 10 months. Any areas that develop during this time might therefore be of special interest in identifying the underlying system of gaze recognition.

Disorders Affecting Gaze

A last point with which human gaze recognition was investigated are disorders and diseases, as they may reveal more about specific processes related to gaze perception. To start with, Keil (2014) noted a case in which a woman gained vision after 12 years of blindness.

Importantly, she was able to learn how to recognise faces. Though it was noted that it was a gradual process, and she continues to make more errors in face recognition, compared to a person with normal vision. This is a clear example of gaze recognition being a skill slowly developed over time. It also shows that adults are still capable of learning this skill to a high degree.

Another example of a disorder related to gaze is autism. In a study by Birmingham et al. (2017), they found no significant difference in time between people diagnosed with autism and neurotypical individuals in gaze recognition. Furthermore, in her research, Birmingham (UBC Education Research, 2014) suggested that social attention might be a two-step process system, split into gaze recognition and gaze following. Notably, children with autism did not differ in the likelihood of gaze following but rather exhibited a slower response time of gaze following. Again, this gives implications of more than one system linked with gaze. Furthermore, this potentially points to gaze following being the more problematic process for individuals with autism. The first step, gaze recognition, may be less susceptible to errors, possibly due to a robust and/or simple mechanism.

Based on all this, what can be said about gaze recognition? Gaze recognition is an intrinsic process that is further refined and learned in our early months of life. There are potentially multiple processes at work, and there are other processes linked to gaze, such as gaze following or facial recognition. Gaze recognition likely evolved along the lines of the cooperation eyes hypothesis, the white sclera of the human eye and the horizontal stretch are related to it. Gaze recognition also seems to be rather robust and precise. Lastly, gaze itself has a direct impact on our emotions.

The Current Study

Building on the presented research, this paper investigates gaze recognition. The aim of this paper is to focus on the mechanism of gaze recognition. For this purpose, an eye tracker will be used as a model for human gaze recognition. However, commercial eye trackers use mechanisms such as the corneal reflection effect. The corneal reflection effect relies on the reflections in the pupil of the eye and either infrared or near-infrared light to calculate a vector between the pupil and the reflection and from this calculates the gaze orientation (Nitschke et al., 2013). This would be highly unlikely to function for a human process, as it is rather complicated, and such a process of calculation would be nearly impossible for humans. Additionally, the light used in this process is, most of the time, not visible to humans.

As such, a different model needs to be used. The "your eye tracker" (YET) eye tracking software from M. Schmettow. The YET will be used since it is based on a quad brightness system. The quad brightness mechanism can be broken down to a 2x2 pixel system with north-east, north-west, south-east and south-west as pixels that use the differences in average light in each of these pixels to determine the gaze orientation. This is a much simpler model that would be perfectly applicable for humans and also fits some of the criteria found related to gaze. For one, humans were able to detect small differences in gaze, e.g. the degree of accuracy, but also small differences in light. Second, the simplicity would account for scenarios such as babies being able to develop gaze recognition early on, as previously established. Lastly, the combination of simplicity and being brightness-based does work with the cooperative eye hypothesis and the general properties of the eye, e.g. white sclera and horizontal stretch.

Hypothesis

There are two hypotheses investigated in this paper. First, humans are able to perceive the gaze orientation based on a simplified quad brightness process. Second, how can the accuracy of gaze estimation of quad brightness be compared to the accuracy of gaze estimation in a naturalistic setting?

Method

Demographic Data and Sample

The data was collected from 31.04.2025 to 02.05.2025 and a total of 43 participants took part. The participants were recruited via convenience sampling, partly with the help of the Sona system. None needed to be excluded.

There are no ethical considerations we are currently aware of that need to be considered. There are exclusion criteria for the study. First, the participants should not suffer from any form of uncorrected visual impairment. Secondly, only participants 18 and above could join. The study was approved by the Ethics Committee BMS (Application no. 250623) of the University of Twente. All participants gave written informed consent before the study in accordance with the Ethics Committee BMS guidelines.

Of the 43 total participants, 25 were assessed by Researcher A and 18 by Researcher B. The average participation time was approximately 15 minutes for Researcher A participants and 22 minutes for Researcher B participants and 18 minutes for all participants combined. The average age of participants was 34,2 years and there were 20 (47%) female and 23 (53%) male participants.

Materials

To build this experiment, photos were shot and manipulated, replacing the eyes with four quadrants, each with the average brightness. The images were shot with a GoPro HERO5 Black (3mm f/2.8 1/60 sec... ISO 881 light setting 0 no lightning, data format 4000x3000 2.2mb 72DPI 24bit) and saved as JPG.

A Velbon eX-630 tripod was used to stabilise the pictures. The camera was positioned slightly below the subject's face, tilted upwards and centred (see Figure 2). Furthermore, the photos were taken indoors with a headlight from above/front and a dimmed light from behind. A greenscreen was used to clear out the background, and an LED lamp

(3500 kelvin, 60 lumens) centred in the middle, below the face, was used to eliminate shadows. Additionally, an LG 55-inch TV displayed a clock, so that the photo model could get an accurate point estimate of where to look. This TV was kept on the lowest light setting to reduce reflection in the iris. Lastly, the model itself was sitting on a chair with their eyes centred in the middle of the screen. This position was kept by a folding ruler that served as a headrest. The face was oriented straight forward. The photo models' eyes were light blue.

Figure 2

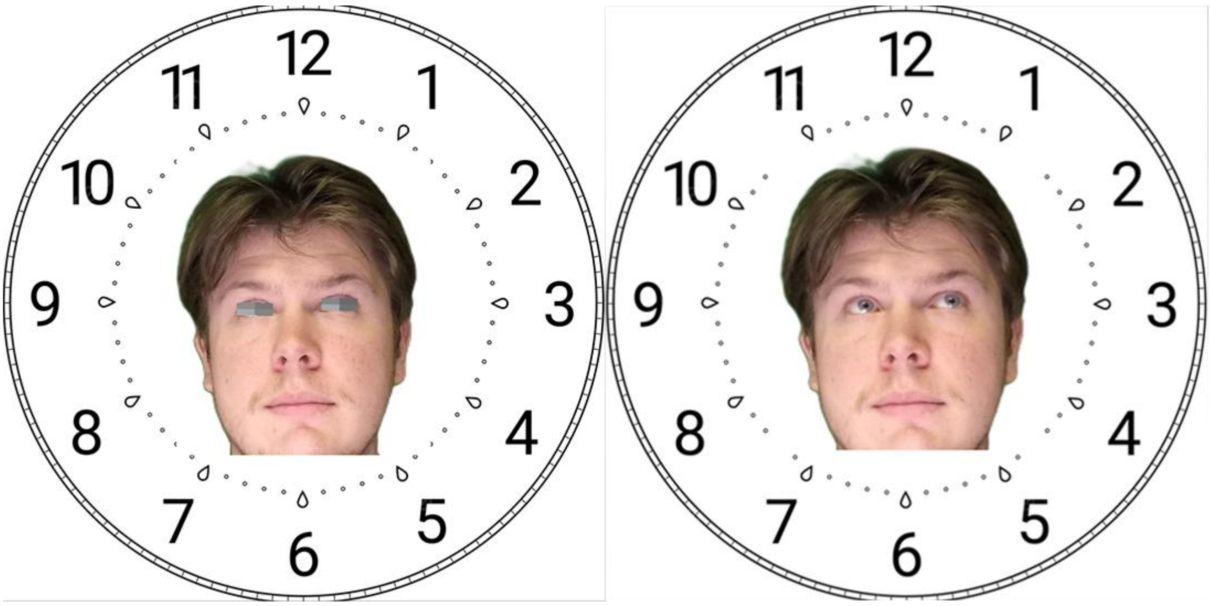
Camera and Photo Model Setup

Between each shot, a record was kept by a separate photographer, both as a picture and spoken aloud, of the next recorded time. With each shot, 5 photos were taken automatically, a second shot followed if the photographer felt that the photo model's eyes were too closed.

After numerous trials, the best photos were selected and run through an algorithm that uses some of the functions of the YET. This algorithm is called “Your Eye Cutter” (YEC), and it detects eyes, sorts each eye into four quadrants, calculates the average brightness of each and lastly crops the quadrants onto the eyes (see Appendix A). These images were used as the manipulated pictures. Afterwards, the photos had to be mirrored, the background was removed, they were zoomed in onto the face and tilted by 1 degree to adjust for a slight natural tilt of the head towards the stimuli. This process was also done for the non-manipulated pictures (see Figure 3). The experiment was run on two different laptops, one with a 17-inch screen and one with a 15-inch screen.

Figure 3

One o'clock in Experimental and Control Conditions



Design

This study was designed to investigate gaze orientation and measure the accuracy of participants, while manipulating the cue duration of the images shown to the participants.

There are three independent variables, of which two are included in the model, the cue time and the condition, e.g. manipulated vs unmanipulated. The gaze orientation is not included in the current study. The dependent variable is the respondent's accuracy (see Table 1).

As independent variables: Gaze orientation with 12 levels, e.g. from 1-12 as hours on a watch. Gaze orientation describes the direction of gaze or the photo model. The model looked at a clock with the corresponding time. Cue time with 5 levels, e.g. 70ms, 140ms, 400ms, 600ms and 1000ms. This is the time the participants were able to see each stimulus. Condition with 2 levels, e.g. control and experimental. In the control, there was a normal face shown, while in the experimental the manipulated faces were used. As a dependent variable, accuracy was measured with values between 0 and 6. This is measured by difference, e.g. if the clock showed 12 and the participant's answer was 1, there is a difference of 1 hour. This, in turn, can be converted into angle difference, e.g. 1 hour equals 30 degrees. All variables were used in a within-subject approach. Each participant was run through all levels and all variables.

During the procedure, the gaze orientation was shown three times per condition and cue time in a full random sample. The condition and cue time were controlled and followed a pattern starting with 70ms experimental, 70ms control, 140ms experimental and so on.

Table 1

Dependent and Independent Variables

Variable	Type	Levels
Gaze orientation	Independent variable	12
Cue Time	Independent variable	5
Condition	Independent variable	2
Accuracy	Dependent variable	0-6

Procedure

Next, the experiment was created using PsychoPy with Version 2024.2.4. In the PsychoPy builder, the experiment flow was made, which followed this stream (see Figure 4). First, a test run, with one example picture, in which the process was explained by the researcher. Second, a confirmation window to start the experiment for participants by clicking the left mouse button, third, a countdown from three down to one, fourth, a block was run in which the stimuli are shown.

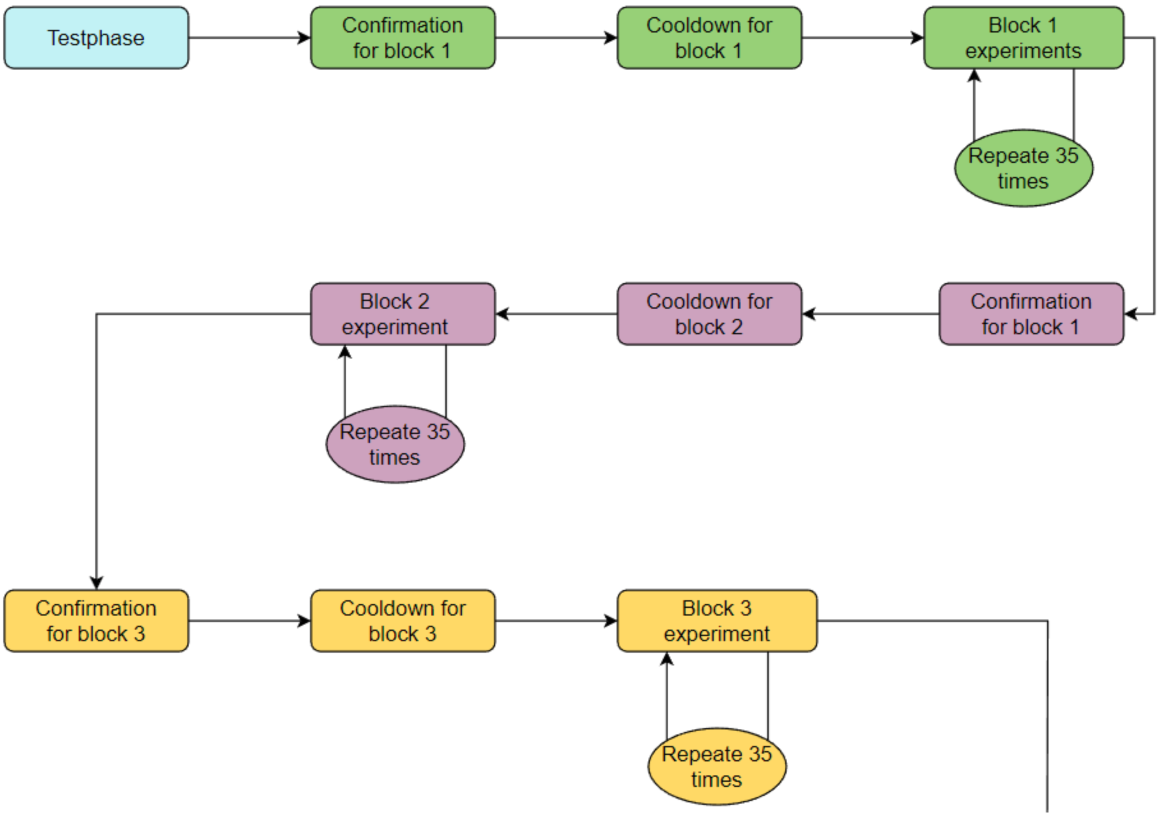
There are twelve stimuli in total in each condition, one per hour/gaze direction. Each stimulus is shown three times per block in a fully randomised order, thus totalling 36 stimuli per block. This is done for five different cue times, e.g. 70ms, 140ms, 400ms, 600ms and 1000ms, as well as for two different scenarios, once with the gaze manipulated into average quad brightness and once with the gaze not manipulated, thus making it in total ten blocks and 360 stimuli in total shown. Between each block is the confirmation and countdown phase again to give participants a possibility to pause/rest. The block will be run in the order of the times presented above, starting from 70, and the scenarios will switch between each block, for example, first block 70ms gaze manipulated, second block 70ms gaze unmanipulated, third block 140ms gaze manipulated, etc. This order is always the same.

During a block, the pictures are shown on the screen, and the participants will then be given a text field in which they can record their estimated gaze direction, this estimate is recorded as a number, e.g. 1 for one o'clock or 9 for nine o´clock.

The distance between participants and laptops was kept at roughly 60 cm. The angle of the monitor was not systematically controlled.

Figure 4

Flowchart for the First three Blocks



Statistical Model

The dependent variable is calculated as follows. The gaze orientation is subtracted from the participant's response. Afterwards, all values are converted into negatives. Next, all values that are below -6 will have a 12 added onto them and all other values are returned to positive values, this ensures that the small angle in a clock is taken.

The data analysis was run on R version 4.5.0 and used RStudio version 2025.05.0+496 for Windows.

For the data analysis, a GLM model was chosen. As a model family a Poisson regression was chosen based on a multilevel design, the discrete properties of the data, as well as a right skew as suggested by Schmettow (Schmettow, 2021).

Result section

Model Setup

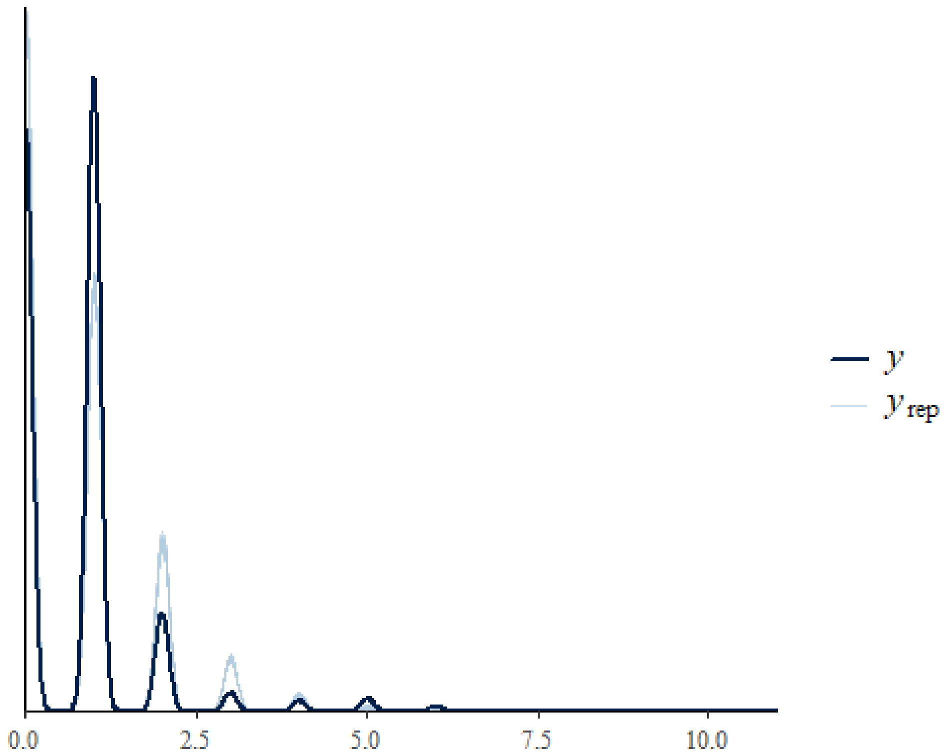
The following Poisson model was fitted.

```
angle_diff ~ condition * presentation_time_ms +
    (condition | participant_number) +
    (condition | stimulus)
```

Prior to interpreting the model, overdispersion was checked. For this, an overdispersion test and a posterior predictive check were run. The overdispersion test showed no overdispersion with a p-value of 1 and dispersion ratio of 0.814, indicating slight underdispersion, if any. Additionally, the posterior predictive check shows a fitting model with the predictive data mostly overlapping with the observed data (see Figure 5).

Figure 5

Posterior Predictive Check

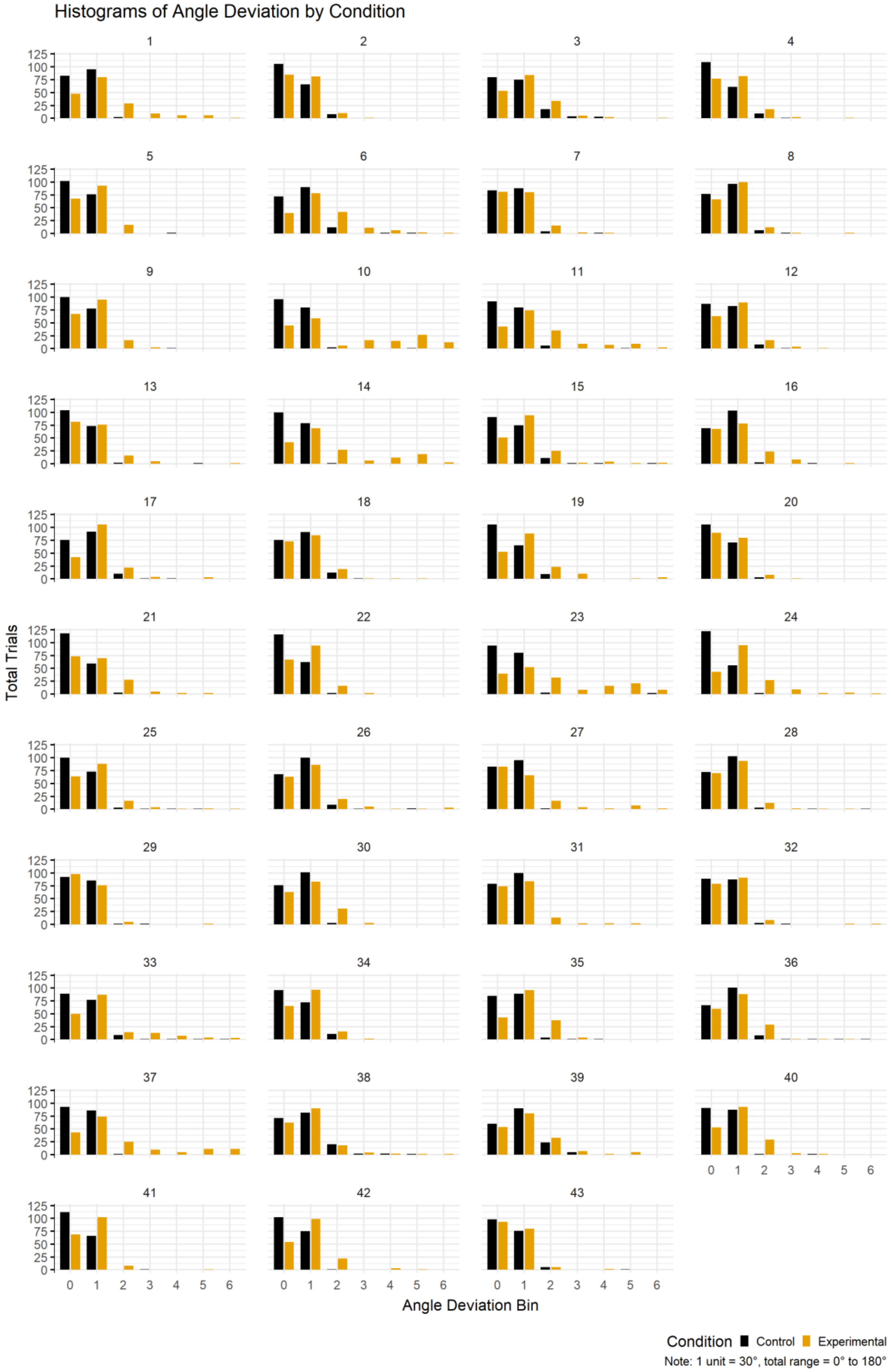


Histograms of Angle Deviation by Condition

Next, histograms were run to visually examine the distribution of the data (see Figure 6). Additionally, descriptive statistics were included. The mean angle difference is 0.755 and the standard deviation is 0.907. Since they are both low, this indicates that most values are between 0 and 1 or 0° and 30°. The histograms show the deviation from 0-6 per participant by condition, notably, each unit means an increase of 30° in deviation. In all graphs, a right skew can be observed. Additionally, a bimodality can be observed. Second, when comparing between control and experimental the control condition is slightly more present in 0 deviations. Furthermore, the experimental condition shows a larger tail towards the higher deviations.

Figure 6

Histogram of Angle Deviation by Condition

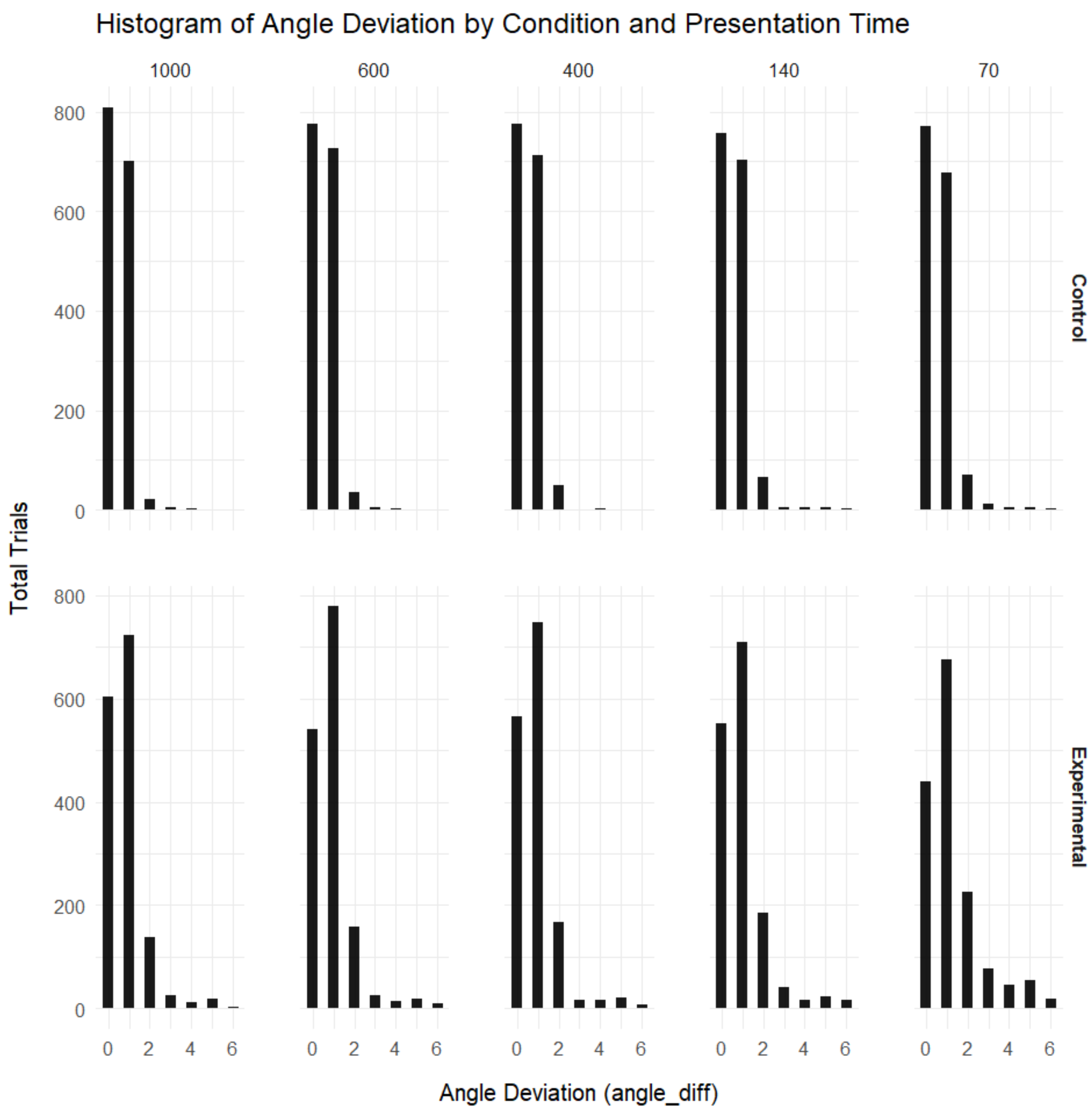


Histograms of Angle Deviation by Condition and Presentation Time

In a comparison between the angel deviation by condition and presentation time, the following points are noticeable. In this setup, the bimodality is still present (see Figure 7). Next, the control condition has fewer deviations than the experimental condition. Furthermore, the tail of the experimental condition increases with a smaller exposure.

Figure 7

Histogram of Angle Deviation by Condition and Presentation Time



Fixed Effects

Next, the fixef function was used to create a table with the exponentiated coefficient was created (see Table 2). With original images and a 1000ms presentation time, the average deviation is approximately 13°. Though, this is only moderately certain, with a credible interval ranging from 10° to 18°. Compared to the control condition, the experimental condition shows a notable increase to approximately 23°. The presentation times of 600ms and 400ms show very little increased deviation to approximately 14°. On the other hand, the presentation times of 170ms and 70ms show a more notable increase to approximately 16°. In the experimental condition, there is less than 1° difference between the base experimental condition and the 600ms and 400ms and, notably, the 140ms conditions. The 70ms experimental condition does, however, differ from the other presentation times of the experimental times. This is the strongest difference aside from the base experimental one, with an increase to approximately 30°.

Table 2

Population-level Exponentiated Coefficient

Effect	Estimate	95% CI Lower	95% CI Upper
Intercept	0.4487513	0.3261372	0.610100
Condition (experimental)	1.6799248	1.2802543	2.219771
Presentation time (600ms)	1.0612134	0.9601286	1.172228
Presentation time (400ms)	1.0673580	0.9673270	1.179895
Presentation time (140ms)	1.1706792	1.0663024	1.290782
Presentation time (70ms)	1.1753459	1.0678440	1.294048
Experimental : Presentation time (600ms)	1.0371618	0.9154754	1.176211
Experimental : Presentation time (400ms)	1.0059389	0.8848574	1.138293
Experimental : Presentation time (140ms)	1.0089375	0.8877376	1.141059
Experimental : Presentation time (70ms)	1.3099123	1.1550963	1.476473

Note. Coefficient estimates with 95% credibility limits

Using the fixef_ml function, a table with the standard deviation of random effects for participants and stimuli is presented (see Table 3). Both have an effect, however, no clear trends can be observed. The standard deviation for participants increases from the control to the experimental condition. On the other hand, the standard deviation for the stimuli decreases from the control condition to the experimental condition.

Table 3

Population-level Coefficients with Random Effects Standard Deviations

Effect	Estimate	95% CI Lower	95% CI Upper	SD Participant	SD Stimulus
Intercept	-0.8012865	-1.1204371	-0.4941324	0.1941792	0.4952715
Condition (experimental)	0.5187491	0.2470586	0.7974042	0.3532580	0.3998600

Note. Coefficient estimates with 95% credibility limits

Stimulus

To further assess whether there are differences in the stimuli group, the following model was made with an additional group used, which grouped the stimuli into vertical or horizontal. The vertical group consists of the numbers 11, 12, 1, 5, 6 and 7, representing the top and bottom numbers of a clock dial. The horizontal group consists of the numbers 2, 3, 4, 8, 9 and 10, representing the numbers on the left and right side of a clock dial. Together, these groups represent the vertical or horizontal gaze orientation. Another fixef table shows the exponentiated coefficient with the horizontal group as intercept (see Table 4). With horizontal and original images, and a 1000ms the average deviation is approximately 12°. However, this is only moderately certain, with a credible interval ranging from approximately 8° to 19°. As with the previous fixef table, a notable increase can be observed. However, more importantly, the inclusion of the vertical grouped images shows a small increase to approximately 13°. Lastly, with vertical images, a 1000ms presentation time and the inclusion of the experimental images, the average deviation shows less than a 1° increase. Overall, no notable difference between horizontal and vertical images was observed.

```
angle_diff ~ condition * stimulus_group + presentation_time_ms +
    (condition | participant_number) +
    (condition | stimulus)
```

Table 4

Population-level Exponentiated Coefficient with Vertical and Horizontal

		95% CI	
Effect	Estimate	Lower	Upper
Intercept	0.411658	0.2639750	0.6418203
Condition (experimental)	1.817189	1.2440758	2.6369004
Condition (vertical)	1.067083	0.5721022	2.0283405
Presentation time (600ms)	1.085570	1.0227012	1.1508603
Presentation time (400ms)	1.072526	1.0100141	1.1406649
Presentation time (140ms)	1.179227	1.1126666	1.2502045
Presentation time (70ms)	1.401865	1.3226830	1.4810413
Condition (experimental) : Condition (vertical)	1.011727	0.6068178	1.6714994

Note. Intercept represents the base group horizontal.

Summary

Based on the provided data, the Poisson model appears to be a well fit for the data. There is no overdispersion and a notable right skew. Additionally, there seems to be no constant random effect.

Hypothesis I: The data showed that the participants were generally able to recognise the gaze direction of the photo model in the experimental condition.

Hypothesis II: There were some differences observed between the control and experimental condition. The experimental condition performed with a 10° increase compared to the control condition, and the experimental condition 70ms performed with a total 17° increase. In the histograms, it is also visible that the condition experimental showed less accurate results with a longer tail towards higher deviation.

Discussion

Research Question

The purpose of this paper was to investigate the human gaze mechanism with quad brightness images. With the aim of finding out whether humans are able to estimate gaze direction from quad brightness images of eyes and to what angular degree the accuracy of such estimations differs from the estimations of unedited images.

Supporting the initial hypothesis, the findings do show that the participants were able to estimate the gaze orientation of eyes manipulated with quad brightness, on a population level. The accuracy of participants was lower in the unedited 140ms and 70ms conditions. Furthermore, there was a general, although small, reduction in accuracy between the unmanipulated and the quad brightness images. This was further pronounced in the 70ms experimental condition but not in the other presentation times in the experimental condition.

Implications

Extending on this, the implications of previous research results on the current results are examined. To start with, Langton et al. (2004) reported in their paper, via multiple studies, the influence of head direction on gaze estimation. They found that when they manipulated the direction of the head while keeping the same eyes with a straight gaze direction, participants reported gaze estimates aligning with the manipulated direction. This effect remained present when they reduced the heads to contours only. Furthermore, Moors et al. (2015) also found evidence for the body playing a role in gaze estimation.

Together, this would give an indication that either the quad brightness is an insufficient model or that there are multiple mechanisms at play that overlap with each other. The results of the accuracies reported and the general capability of participants to estimate gaze orientation in the current study support the second option. As such, quad brightness would be one of multiple mechanisms. The second option is also indicated by Langton et al.

(2004) who proposes a system integrating information of gaze direction based on the white sclera and head direction, as well as previously noted research such as Keil (2014) describing two systems in infants for face recognition or Birmingham (UBC Education Research, 2014) with the proposed two-step-process system for social attention.

The possibility of a dual system, as well as the head direction having an influence on human gaze estimation, can also be linked back to the cooperative eye hypothesis. As previously stated, Tomasello et al. (2007) described human infants relying more on eye movements than great apes. However, they still reacted to head movements as well. Furthermore, Whitham et al. (2024) found that both humans and primates looked at the eyes of prey and predators, with humans focusing less on other facial features. In the context of the cooperative eye hypothesis and the results of this paper this is an indication of the cooperative eye hypothesis being likely. With humans evolving an additional eye-based system due to cooperation, yet still having a similar system to primates relying on head movement. The current study did not investigate head direction and whether head directions or gaze orientation have a larger impact on gaze estimation. However, the result showed that humans are accurate in estimating gaze solely based on the gaze orientation of another human. Therefore, supporting the assumption that gaze orientation is a cue to estimate gaze direction and a potential evolutionary drive. Lastly, based on these findings, it is not yet possible to say whether there are multiple or separate systems.

Another aspect worth considering is that the accuracy reported does not take into consideration human limitations and errors. As previously reported, the findings of Bock et al. (2008) indicated an accuracy for estimations of gaze orientations of approximately 3°. This has two implications. One the actual accuracy is probably slightly better than in the current findings if the 3° are subtracted due to natural error. Second, there is still a difference between the accuracy found in the conditions with normal pictures, which had an accuracy of

13°, and the reported finding of 3° by Bock et al. As such, there might be additional sources of error. While the random errors showed no consistent trend, they did show a possible increase of error due to the specific stimuli and/or participants. This should be considered as both a potential noise in the results and an area of improvement in future research.

Similar findings were reported by Clifford and Palmer (2018) in relation to the gaze aftereffects. These aftereffects seem to alter humans perceived direction of gaze orientation. The manner in which they do this was described by Clifford and Palmer as repelled, meaning that when an averted gaze is shown, subsequent gazes were perceived as more likely in the opposing direction. Notably, this effect has been reported as an issue related to the *high-level* processing of gaze estimation. As such, there is a chance that this does not affect the quad brightness mechanism as it is a simple mechanism and likely operates on the *low-level* to *midstream*. This will be further addressed in the limitations with masking.

A last angle that will be discussed are optical illusions. Specifically, Jenkins (2007) created an illusion of a face (see Appendix B). Close up, about 40 cm, people will estimate a person looking to the left, while from further away, about 3m, people will estimate a person looking to the right. This was done by matching two images with different grayscale values. The theory behind this being that luminance distribution influences gaze estimation. This is a conceptually similar process to the quad brightness mechanism. However, the quad brightness mechanism would be slightly more sophisticated. Furthermore, this also adds the potential of distance as a research metric for quad brightness. Lastly, the author also indicates the possibility of more than just a mechanism for luminance distribution being used for gaze recognition.

Limitations

There are a few considerations and limitations that need to be considered. Firstly, there were no visual masks used. This means that the presented stimuli might still linger as afterimage in the phenomenon called visual persistence (Breitmeyer, 2007). A mask would limit the exposure time and as such, allow for a more precise interpretation of the results. Furthermore, while there is only a possibility that the aftereffects reported by Clifford apply to the current experiment, a mask might have ensured that these have no effect. As such, while it is true that the absence of masking created a more natural experiment, this still limits how the exposure times, particularly the lower exposure times, can be interpreted.

On a similar note, the findings of Langton et al. (2004) should be considered. In their research, they found influences of facial asymmetry on gaze estimation. Specifically, they manipulated the nose to distort it in one direction and measured the effect of this asymmetry on gaze estimation. Additionally, they note that this effect is smaller compared to the effect produced by head direction and is affected by inversion. As such, there is a possibility that the asymmetry of the photo model's face introduced noise in a specific direction. While naturalistic faces are closer to reality, a clearer result could be found when investigating the quad brightness with averaged faces. As these are much more symmetric and therefore allow for a controlled setting in which this noise could be eliminated.

Additionally, no after-survey was conducted. Thus, there is no recorded data from participants afterwards with possible points of improvement or criticism. While some accounts were still collected by researchers in a discussion afterwards, this was not done systematically by any means. Potential research questions in this direction can be both quantitative as well as qualitative. Quantitative questions could include rating the performance, how well the participants believed they were able to see the pictures or the difficulty of the task on a Likert scale. Qualitative questions could include “Were some images easier to interpret and why?”, “Did something affect your ability to judge the images?”, “What methods or strategies did you use to estimate the gaze orientation?” or just general feedback. These questions could give additional information that might provide insights into both the findings as well as possible problematic areas. Additionally, these questions would provide further data which are not currently collected by the experiment directly. As such, they might help by pointing out faulty stimuli or show a blind spot of the researchers.

The accounts that were taken revealed the following points of criticism. Firstly, the pictures at the start were very fast. This could be adjusted by giving more training rounds at the start. Secondly, some participants noted that they learned the faces and knew roughly where the person was looking in the picture. If this effect is indeed present, this would affect the results and should therefore be adjusted in future research, for example, by incorporating a variety of faces from different individuals or using several variations of the same face for one specific time, for example, four different photos for 12 o'clock.

Considering the photos, it should be noted that the headrest used for the photos was improvised and, as such, might have resulted in a natural tilt. This could be avoided by using a proper headrest.

Future Research

For future studies, multiple possible approaches can be taken, based on the results confirming the quad brightness to generally function for humans. For one, the universality of this claim could be tested on individual participants. Second, when the quad brightness mechanism models our own mechanism, it should work in a variety of settings. As such the following settings could be explored. One example would be light. This could be done by adjusting the light within the eye to find the absolute threshold at which people are able to reliably make gaze estimations with the quad brightness condition. For example, pictures could be shown of faces with quad brightness eyes in fully white and participants can manually increase the fill by a small percentile. This is repeated till they believe to estimate the gaze direction.

Another example is head directions related to the findings of Langton et al. (2004). Again, the quad brightness mechanism could be further investigated to confirm whether it still functions in certain conditions. Here it could be checked what kind of influence head directions have on quad brightness, if quad brightness still functions reliably and whether there are multiple and more importantly combined or separate systems at work for gaze estimation. This could be further pushed with the use of just head contours, allowing for a situation in which only the most simplistic information is given from both studies, e.g. quad brightness for the eyes and contours for the head.

Videos could push this research even further. Given that the quad brightness should not only work in still images but in a real-life situation, a video or VR setting with a short clip or animation could be made to test whether humans are still capable of estimating gaze in such a situation accurately.

Possible use Cases Implications

Given that the first hypothesis was confirmed, this would open the option to use this mechanism in investigating the development of gaze recognition in children or potentially close related primates. This might add further context to these studies and explain unclear factors. Moreover, this might open up possibilities to model the different systems used and needed to learn gaze recognition and potentially shared gaze. As such, this may also be of interest to autism research as the implications of a two-process system by Birmingham et al. (2017) combined with this mechanism might help to give insight in how certain processes work differently in certain groups, as only robust models are able to build accurate and lasting help. On a similar note, the knowledge of how this process functions could also be used in rehabilitation for a person suffering a form of blindness e.g. such as in the case of Keil (2014) with a woman gaining sight only after more than 10 years of blindness and having to learn face recognition from scratch.

Conclusion

In summary, this study proved that quad brightness is a possible model mechanism for human gaze estimation and, as such, offers the possibility of a new and unique investigations into human gaze. While the result indicated lower accuracy of the quad brightness compared to original images and no visual mask was used, limiting the interpretation somewhat. The overall accuracy was still sufficient to indicate quad brightness as a fitting model.

Combining these results with current research, there is a broader implication of multiple systems interacting with gaze. Whether these are separate or not cannot be said as of yet. However, this does open new angles of investigation for cognitive psychology, particularly whether there is a combined or separate system and how these might work, and also in the direction of autism research, investigating the interaction of these systems and the implications for autism and other disorders.

As future research delves deeper into the mechanisms of human gaze, quad brightness has the potential to become a valuable model in the study of gaze estimation.

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Appendix A

Your Eye Cutter (YEC)

Python code that takes an image, detects the eyes and crops a quad brightness image onto the original images. This was together with my colleague Janis Hölter.

```
import cv2 as cv
import numpy as np
import os


# Define input and output directories
input_dir =
r"C:\Users\minko\Documents\Uni\M12\Yet\Experiments\Rawmaterial\60_Seconds"
output_dir = r"C:\Users\minko\Documents\Uni\M12\Yet\Experiments\Edited_material"
os.makedirs(output_dir, exist_ok=True)  # Ensure the output directory exists


# Get list of image files in input directory (only JPG and PNG)
image_files = [f for f in os.listdir(input_dir) if f.lower().endswith(('.jpg', '.png'))]
image_files.sort()  # Sort to maintain order


#YEC takes and jpg or png image and detect the eyes with the image.
#For each eye the average brightness is calculated and croped onto the eyes, split into four
regions.
#To make this programm functional the file directionary in line 29 needs to be changed, the
image is stored in the current directionary.


def quad_bright(frame):
```

```
    """Splits an image into four quadrants and calculates their average brightness."""
    h, w = frame.shape  # Get dimensions (height first in OpenCV)

    NW = np.mean(frame[0:int(h / 2), 0:int(w / 2)])
    NE = np.mean(frame[0:int(h / 2), int(w / 2):w])
    SW = np.mean(frame[int(h / 2):h, 0:int(w / 2)])
    SE = np.mean(frame[int(h / 2):h, int(w / 2):w])

    return (NW, NE, SW, SE)

def generate_brightness_image(brightness, size):
    """Creates a grayscale image filled with a given brightness value."""
    img = np.full(size, int(brightness), dtype=np.uint8)
    return img

# Load Haar cascades
"""Uses eye_cascade as this is more precicse, but this does not work with glasses."""
face_cascade = cv.CascadeClassifier(cv.data.haarcascades +
"haarcascade_frontalface_default.xml")
eye_cascade = cv.CascadeClassifier(cv.data.haarcascades + "haarcascade_eye.xml")

# Process each image in the folder
for i, filename in enumerate(image_files, start=1):
    image_path = os.path.join(input_dir, filename)
    image = cv.imread(image_path)
```

```
    if image is None:
        print(f"Error: Could not read {filename}. Skipping...")
        continue

    # Convert to grayscale
    gray = cv.cvtColor(image, cv.COLOR_BGR2GRAY)

    # Detect faces in the image
    faces = face_cascade.detectMultiScale(gray, scaleFactor=1.3, minNeighbors=4)
    print(f"Processing {filename} - Detected faces: {len(faces)}")

    # Loop over detected faces
    for (x, y, w, h) in faces:
        roi_gray = gray[y:y + h, x:x + w]  # Face region in grayscale
        roi_color = image[y:y + h, x:x + w]  # Face region in color

        # Detect eyes in the face region
        """scaleFactor checks for false positives minNeighbors for false negatives minSize can
be used to exclude false detection such as noses"""
        eyes = eye_cascade.detectMultiScale(roi_gray, scaleFactor=1.3, minNeighbors=10,
minSize=(40, 40))

        if len(eyes) == 0:
            print("No eyes detected in this face.")
```

```
# Loop over detected eyes
"""uses an enumerate to keep track of item and index"""
"""rename ex, ey, ew and eh to allign better with inital NW, NE, SW, SE"""
for (ex, ey, ew, eh) in eyes:
    # Crop the eye region (excluding unnecessary parts)
    crop_start_y = max(0, int(ey + 0.36 * eh))
    crop_end_y = min(h, int(ey + 0.64 * eh))
    crop_start_x = max(0, int(ex + 0.15 * ew))
    crop_end_x = min(w, int(ex + 0.95 * ew))
    eye_region = roi_gray[crop_start_y:crop_end_y, crop_start_x:crop_end_x]

    # Ensure cropped region is valid
    if eye_region.size == 0:
        print("Warning: Eye region is empty after cropping. Skipping...")
        continue

    # Compute brightness
    """check if we should use percived brigthness?"""
    quadrants = quad_bright(eye_region)

    # Generate quadrant brightness images
    h_half, w_half = eye_region.shape[0] // 2, eye_region.shape[1] // 2
    quad_images = [
        generate_brightness_image(quadrants[0], (h_half, w_half)),  # NW
```

```
            generate_brightness_image(quadrants[1], (h_half, w_half)),  # NE
            generate_brightness_image(quadrants[2], (h_half, w_half)),  # SW
            generate_brightness_image(quadrants[3], (h_half, w_half))   # SE
        ]

        # Stack quadrants to create final brightness image
        top_row = np.hstack((quad_images[0], quad_images[1]))  # NW | NE
        bottom_row = np.hstack((quad_images[2], quad_images[3]))  # SW | SE
        quadrant_img = np.vstack((top_row, bottom_row))  # Full quadrant image

        # Resize quadrant image to match detected eye size
        quadrant_img = cv.resize(quadrant_img, (crop_end_x - crop_start_x, crop_end_y -
crop_start_y))

        # Insert quadrant image back into original eye position
        roi_color[crop_start_y:crop_end_y, crop_start_x:crop_end_x] =
cv.cvtColor(quadrant_img, cv.COLOR_GRAY2BGR)

    # Save the modified image with a sequential number
    output_image_path = os.path.join(output_dir, f"{i}.jpg")
    success = cv.imwrite(output_image_path, image)
    if success:
        print(f"Saved modified image as {output_image_path}")
    else:
        print(f"Error: Could not save {output_image_path}")
```

```
print("Processing complete.")
```

Appendix B

Gaze illusion

This Figure was used with the permission of Rob Jenkins. The optical illusion becomes visible by either blurring your vision or moving about 3m away from the image.

Appendix C

Informed Consent

This is the informed conset form given to the participants. This is a adaptation of the template given out by the University of Twente.

Consent Form for *How do humans perceive gaze direction*

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated [/ /], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions, and I can withdraw from the study at any time, without having to give a reason.	○	○
I understand that taking part in the study involves collecting my age and gender as well as anonymous responses given during the experiment	○	○
Use of the information in the study		

I understand that information I provide will be used for writing a bachelor thesis and building potential future research questions ○ ○

I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team. ○ ○

Future use and reuse of the information by others

I give permission for the data, age and gender, that I provide to be archived in an excel file so it can be used for future research and learning. ○ ○

Signatures

______________________ ______________________ ________

Name of participant

Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

_________________________ ___________________ ________

Researcher name [printed] Signature Date

Study contact details for further information:

Julian Großerichter j.groserichter@student.utwente.nl

Janis Hölter j.holter@student.utwente.nl

Contact Information for Questions about Your Rights as a Research Participant: If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee/domain Humanities & Social Sciences of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-hss@utwente.nl

Appendix D

R Code

This is the code used in the Data analysis. This code uses the bayr package by M. Schmettow for further information please refer to his github as well as the book New statistics for design researchers A Bayesian workflow in tidy R Section 7.2.1 Poisson regression.

```
install.packages("ggpattern")
library(ggpattern)
library(brms)
library(tidyverse)
library(devtools)
library(rstanarm)
library(ggplot2)
library(bayr) #needs to be run after rstanarm according to book
library(performance)
library(bayesplot)

data <-
    read.csv("C:\\Users\\minko\\Documents\\Uni\\M12\\Yet\\Experiments\\Cleaned_data\
    \dataset_cleaned_43.csv")

# Security checks
colnames(data)

summary(data)
```

```
# Checks if there is a correct amount of stimuli
table(data$stimulus)

#Note this was multiplied by 30 but is later returned to normal values, due to issues with the
    model
#create the angle_diff varaible
data$angle_diff <- (data$stimulus * 30) - (data$response * 30)
data$angle_diff <- ifelse(data$angle_diff > 0,
            -data$angle_diff,
            data$angle_diff)

#important since we use the "small" clock angle this need to be adjusted as the angle could
    otherwise be a large angle
data$angle_diff <- ifelse(data$angle_diff < -180,
            data$angle_diff + 360,
            abs(data$angle_diff))

# converts values back to values between 0-6 as the multiplied values created an
    overdispersion
data$angle_diff <- data$angle_diff / 30

# Make categorical variables into factors
data$condition <- as.factor(data$condition)
data$presentation_time_ms <- as.factor(data$presentation_time_ms)
```

```
data$participant_number <- factor(data$participant_number)
data$stimulus <- factor(data$stimulus)



# Reverse the factor levels of presentation_time_ms
unique(data$presentation_time_ms)
data$presentation_time_ms <- factor(data$presentation_time_ms,
                                    levels = rev(c("70", "140", "400", "600", "1000")))
# To check the data
summary(data$presentation_time_ms)

saveRDS(data, file = "prepared_data.rds")
file.exists("C:/Users/minko/Documents/prepared_data.rds")

# Enables 6 cores for faster computation note this referees to physical cores so 6 cores use 12
      cores total. Leave 2 cores over so pc does not crash again
options(mc.cores = 6)

# Fit the model most complex model
M <- stan_glmer(angle_diff ~ condition * presentation_time_ms + (condition |
      participant_number) + (condition | stimulus),
        family = poisson,
        data = data)
```

```
#Save model
saveRDS(M, file = "model_fit.rds")

M <- readRDS("model_fit.rds")

formula(M)

# Check for overdispersion
check_overdispersion(M)
pp_check(M, type = "stat", stat = "sd")

#Fixed effects
fixef(M)

#Only this tables maters
fixef(M, mean.func = exp)

#Histogramm section

summary(data$angle_diff)
#sd
cat("Standard Deviation of angle_diff:", round(sd(data$angle_diff, na.rm = TRUE), 3), "\n")
```

```
#Created bins so that the distance for the position dodge functions is always the same. Note
        only create bins specifically for the amount of deviations otherwise it goes infint.
bin_breaks <- seq(0, 7, by = 1)       # breaks: 0, 1, ..., 7
bin_labels <- as.character(0:6)      # labels: "0", "1", ..., "6"

binned_data <- data %>%
  mutate(bin = cut(
    angle_diff,
    breaks = bin_breaks,
    labels = bin_labels,  # use clean numeric labels
    include.lowest = TRUE,
    right = FALSE
  )) %>%
  count(participant_number, condition, bin) %>%
  complete(participant_number, condition, bin, fill = list(n = 0))

ggplot(binned_data, aes(x = bin, y = n, fill = condition)) +
  geom_col(position = position_dodge(width = 0.8), width = 0.7)+
  scale_fill_manual(values = c("Control" = "#000000", "Experimental" = "#E69F00")) +
        #uses colourblind and black and white friendly colours
  facet_wrap(~ participant_number, ncol = 4) +
  labs(
    title = "Histograms of Angle Deviation by Condition",
    x = "Angle Deviation Bin",
```

```
  y = "Total Trials",
  fill = "Condition",
  caption = "Note: 1 unit = 30°, total range = 0° to 180°"
 ) +
 theme_minimal(base_size = 32) +
 theme(
  axis.title.x = element_text(margin = margin(t = 15)), #Margins for the labels
  axis.title.y = element_text(margin = margin(r = 15)),
  axis.line.y = element_line(color = "black", linewidth = 0.9),
  axis.ticks.y = element_line(color = "black"),
  strip.text = element_text(size = 26),
  panel.spacing = unit(3.2, "lines"), #more panel spacing so that the participant numbers do
      not get mixed up
  legend.position = "bottom",
  legend.justification = "right",  # aligns to bottom-right
  legend.box.just = "right",       # aligns contents of the box
  legend.direction = "horizontal", # puts items in a row
  legend.margin = margin(t = 10)
 )


#Second histogram
levels(data$condition) <- c("Control", "Experimental")
```

```
ggplot(data, aes(x = angle_diff)) +
  geom_histogram(fill = "black", alpha = 0.9, binwidth = 0.5) +
  facet_grid(condition ~ presentation_time_ms, scales = "free_y") +
  labs(title = "Histogram of Angle Deviation by Condition and Presentation Time",
       x = "Angle Deviation (angle_diff)",
       y = "Total Trials") +
  theme_minimal(base_size = 15) +
  theme(
    axis.title.x = element_text(margin = margin(t = 15)),
    axis.title.y = element_text(margin = margin(r = 15)),
    strip.text.x = element_text(size = 12),
    strip.text.y = element_text(face = "bold", size = 13),
    panel.spacing = unit(2.5, "lines")
  )


#Randomeffects
fixef_ml(M)



#random effects of stimuli


# Convert factor to numeric
# data$stimulus_number <- as.numeric(as.character(data$stimulus))
```

```
# Create new column for stimulus group
# data$stimulus_group <- ifelse(data$stimulus_number %in% c(11, 12, 1, 5, 6, 7),
#                               "vertical",
#                               "horizontal")

M_stimuli <- readRDS("C:/Users/minko/Downloads/model_stimuli.rds")

formula(M_stimuli)

fixef(M_stimuli, mean.func = exp)
```

Appendix E

AI Statements

These are the programs used during the creation of this thesis.

During the preparation of this work the author(s) used Adobe Photoshop 2025 in order to modify pictures. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work the author(s) used Microsoft Word in order to Write and correct simple spelling mistakes. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work the author(s) used ChatGPT in order to Brainstorm ideas, find synonyms, receive feedback on my own text, assistance in programming my ideas in both Python and R. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work the author(s) used Psychopybuilder in order to create an experiment. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work the author(s) used PyCharm in order to create the YEC program. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work the author(s) used EndNote 20 in order to sort my references and create my reference list. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work the author(s) used R Studio in order to write my data analysis in R. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work the author(s) used Excel in order to Sort my data. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work, the author(s) used Google drive in order to organise notes and code with my study partner. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work, the author(s) used Grammarly in order to correct spelling. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work, the author(s) used Scribbr in order to prevent plagiarism. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

During the preparation of this work, the author(s) used Plagiarismdetector in order to prevent plagiarism. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.