Short Report

PERCEPTION

Examining Gaze Cone Shape and Size

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Abstract
Another person's looking behavior is used by observers to judge gaze direction and fixation points. An important task in this context is the judgement of direct gaze, that is, the perception of being looked at. The cone of gaze can be defined as the range of fixation points that support direct gaze. The cone concept implies that this range lawfully increases with distance, but that the cone angle is constant. The present experiment tested the concept with a larger number and a more extended range of distances than previously done, and took care of possible directional errors. The gaze cone was found to be roughly linear, and stable between 1.6 m and 7.9 m – an almost perfect cone. The mean cone size subtended 5.2° in diameter when averaged over ascending and descending series. Measures differed, however, in ascending and descending series, consistent with a conservative bias. Also, the variability of judgements increased slightly with distance. Results are discussed considering whether cone size is actually smaller than often reported in the literature.

Keywords
perception, face perception, social cognition, gaze perception, gaze cone, animal signaling

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Introduction

While looking is primarily instrumental for the looker, the concomitant eye movements are nonetheless visible to observers, and thus communicative in an "animal signaling" perspective (Maynard-Smith & Harper, 1995). Actually, as the human eye features an especially large and light sclera that visually contrasts with the pigmented iris and the enclosed dark pupil, which is not the case in other primate species, some theorists have proposed that the eyes are communicative by design (Kobayashi & Kohshima, 1997, 2001). Why should an observer care about the eyes? Given that the eyes target areas that provide information required by the task of the looker (for an overview, see Tatler et al., 2011), the observer may learn a lot about the looker's intentions, interests, and concerns. Of course, eye movements do not directly convey the dwellings of the mind; however, because the rotations of the eyes – a physical dimension – and the direction of the

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gaze – as a psychological dimension – are highly correlated (e.g., Deubel & Schneider, 1996) and connected by physical principles, eye rotation is semiotically an index (in contrast to an icon or a symbol) for gaze direction (Maynard-Smith & Harper, 1995).

Experimental gaze perception research has studied the ability of humans to perceive gaze direction from the visible changes of eyeball rotation. Direct gaze – when the looker is looking at the observer, usually at the face or the eyes – is perceived with high acuity, and even small deviations from straight gaze are sufficient for gaze to be perceived as averted (Gibson & Pick, 1963). Research has also examined triadic judgement tasks (West, 2015), where the object of the looker's gaze is not the observer, but a separate ("third") object. People's judgements of gaze direction in triadic tasks demonstrate their good sensitivity to eyeball rotation; however, their judgements are often troubled by an overestimation bias (Anstis et al., 1969) of about 50% (lower values are reported by Masame, 1990, but even higher ones by West, 2011). In other words, triadic judgement is precise (reliable), but not quite accurate (valid). For example, horizontal eyeball rotations of 5 and 10 degrees are perceived as gaze directions of 7.5 and 15 degrees, respectively. If the head is rotated as well, this overestimation bias is accompanied by the head-turn effect (or probably more to the point: the overcorrection effect), where the correction of the head turn overshoots, resulting in a perceived shift of gaze direction in the opposite direction of the head turn (e.g., Anstis et al., 1969).

The perception of eyeball rotation has been found to be quite sensitive: Symons et al., 2004, report thresholds of 1 degree rotation for a looker-observer distance of 1 m in a triadic judgement task; this translates to the discrimination of a 0.1 mm difference in the position of the iris between the straight and the averted gaze direction. Yet, often the perfect perception of small differences in eyeball rotation is not exactly what is needed in natural communicative situations. When two interactants speak face-to-face, it is common that the speaker looks at the face of the listener and that the listener looks at the face of the speaker, at least intermittently (Kendon & Cook, 1969). As the target here is not a point, but rather an area, it follows that the range of gaze directions that are accepted to be on target is larger than for a point (as measured by Symons et al., 2004). Thus, theorizing about the judgement of being looked at has been more recently extended using the gaze-cone concept. As developed by Gamer and Hecht (2007), the gaze cone is the range of gaze directions of a looker where the observer judges that the looker is looking at him. This range is limited by the threshold that separates being-looked-at judgements and being-not-looked-at judgements. The central tenet of the gaze-cone concept is that this range of gaze directions is defined in terms of a single visual angle, with the consequence that the width of the area at different distances increases, whereas the visual angle is constant. The authors suggest the gaze cone to be about 10 degrees wide, including an area spanning 18 cm at a distance of 1 m and, correspondingly, an area of 87 cm at a distance of 5 m. The gaze cone might be somewhat smaller than that, yet, as some experiments found gaze cones with diameters about 5 degrees (Gamer & Hecht, 2007, Exp. 4; Gibson & Pick, 1963).

The present research seeks to extend the previous work in three respects. First, Gamer and Hecht (2007) tested their gaze cone concept with only two looker-observer distances, 1 m and 5 m. Two distances, however, give only limited information on the shape of the gaze cone, whether it is characterized by a constant angle and is thus independent from distance, or whether the cone size shrinks or expands. Actually, Gamer and Hecht's data reveal a trend towards a shrinking cone size, in particular with the human stimulus. The present experiment strives to yield more information on the cone shape by testing 6 distances rather than the 2 distances of Gamer and Hecht. Moreover, the distances cover a different and more extended range than before between 1.6 m and 8 m. Second, Gamer and Hecht (2007) measured the gaze cone size with descending series only (i.e., move the eyes to the point where you no longer feel being looked at). While doing so is certainly sufficient to compare gaze cone size between different conditions, it might be not optimal in obtaining information about the actual size of the cone. Measuring descending series only may lead to inflated measures if, for example, the observers judge conservatively. The natural solution to avoid hysteresis is to measure thresholds with ascending and descending series. Assuming that conservative tendencies in judgements are present in both series, averaging thresholds obtained by ascending and descending should cancel out directional biases. Finally, we analyzed the variability of judgements within participants. The variability of judgements can be seen as an index of the observer's uncertainty. Previous research has shown that variability increases, for example, when the contrast of the stimulus is reduced (Mareschal et al., 2013). While it is rather obvious that uncertainty increases with looker-observer distance at some point, we tested specifically whether this occurs already within the range manipulated in this research.

To summarize, the aim of the research was to test the constancy of the gaze cone for a wide range of viewing distances, increase the accuracy of the threshold measurement by using ascending and descending series, and measure variability as an index of uncertainty.

Methods

Participants

15 participants, 8 women and 7 men, between 20 and 54 years (mean = 27.1) participated in the 90 min experiment. They had normal acuity and passed a color deficiency test (TITMUS VISION TESTER Petersburg, Virginia, 23803). The participants received course credit or candy for their participation, and they gave written informed consent before participation; the experiments were approved by Bielefeld University's ethics committee and complied with the ethical guidelines of the German Psychological Association (DGPs), and with the provisions of the World Medical Association Declaration of Helsinki.

Stimuli

Stimuli were obtained with a Canon EOS 1100D from a distance of 160 cm. The camera was positioned just above a laptop computer (Acer Aspire 3, with a screen width of 36.3 cm). Connected with the laptop computer was also a second screen (60 cm width), which was positioned behind the looker model. The looker model was a female student with brown eyes. She was instructed to look at a colored cursor (0.5°) and to follow the cursor with the eyes as it moved horizontally. The cursor traveled along a green horizontal line that was visible throughout the trial. The cursor was a circle (20 pixels) with short vertical whiskers (40 pixels as measured from the center of the circle) attached to it, and the inside of the circle flickered green and red to facilitate fixation. To minimize the distance between the cursor and the camera, the cursor was presented just below the edge of the screen, and the screen was tilted backwards to further reduce the vertical distance between camera and cursor. To synchronize the camera with the movement on the monitor, the start and the end of the movement was signaled by a visual event on the second monitor behind the looker model. The horizontal movement used almost the entire screen width and had an extension of 32.5 cm (11.48° for the looker model). A custom written Python script controlled the presentations on the two screens. Two movements were recorded, from left to right, and after a short pause, from right to left.

The stills from the videos were extracted for further processing. First, the sequences were selected such that they included only the period during which the marker stimulus moved. As described before, the movement onset and offset were indicated by a visual marker stimulus behind the looker and thus visible in the video stills. The relevant subsequence was identified, including all stills that immediately followed (for the start) or preceded (for the end) the visible marker stimulus. The left to right sequence comprised 87 stills, and the right to left sequence 86 stills (each still thus represents an eye rotation difference of 1/8 degree of visual angle, or 8 min of visual angle). The stills were centered at the point equidistant between the eyes and on level with the pupil, cropped to fit the head size vertically, and resized to 1024*768, all using the Python module PIL. Three examples of the final stills are depicted in Figure 1. The visible head (including hair) covered roughly a circle with a diameter of 24 cm on the monitor; the eye distance was 6.1 cm. This means that the head subtended visual angels of 8.58°, 6.23°, 4.57°, 3.29°, 2.39°, 1.75°, and the eye distance visual angles of 2.18°, 1.59°, 1.16°, 0.84°, 0.61°, 0.44°, for the distances of 159 cm, 220 cm, 300 cm, 418 cm, 575 cm, and 790 cm, respectively. The visible eye measured 2.0 cm (ranging from 0.72° to 0.14°), and the iris 1.13 cm (ranging from 0.41° to 0.08°; measures for both eyes were averaged).

Because of possible directional errors (e.g., the eye may trail the moving stimulus in the recordings), in addition to the original sequence order, a reversed sequence order was generated for presentation. That is for a left to right movement during recording, the original left to right sequence may be used or the reversed movement, forming an alternative right to left movement of gaze. Any constant directional error would cancel out when the average is computed over both the original and the reversed order. Furthermore, because small imbalances could lead to perceived head turns that may change perceived gaze direction (West, 2013), mirror image series were used in addition to the non-mirrored series.

Apparatus

The stimuli were presented on a 19 inch (35 × 32 cm) LCD-monitor @1280*1024 pixels connected to a microcomputer operated by Linux. The presentation and the response registration were controlled by a custom written Python script using routines from PsychoPy (Peirce, 2007; 2009) where possible. Responses were collected as key presses from a connected USB keyboard. The keyboard was positioned on a table in front of the participant. The monitor and the computer were placed on a heavy cart, which could be placed 159, 220, 300, 418, 575, 790 cm away from the participant.

Design

The task of the observer was to adjust gaze such that he feels "just gazed at" for to-center movements (ascending series) and "just not gazed at" for from-center movements (descending series). The dependent variable was the eccentricity of the gaze that was confirmed by the participant as identifying the threshold. Distance was blocked, and within the distance blocks, the four conditions resulting from a combination of judgement directions (descending/from-center vs. ascending/to-center) and side (to-left and to-right) formed a mini block. Each of the four nested mini blocks within each distance block comprised 16 trials, four repetitions of the factorial

Figure 1. Three stills from the sequence right to left, corresponding to −5.8°, 0° and 5.8° of gaze direction.

combination of 2 (series order: straight vs. reverse) x 2 (mirror: original vs. mirrored). The order of the distances was randomly computed anew for each participant. Each distance-block had an individually randomized sequence of the four conditions (a) descending/center start, move eyes to the left, (b) descending/center start, move eyes to the right, (c) ascending/periphery start (from the right), move eyes to the left, (d) ascending/periphery start (from the left), move eyes to the right. The trials in each mini block were fully randomized. There were 3 practice series used to explain the task and to familiarize the observers with the setting.

Procedure

Each distance block began with the distance code for the experimenter, who moved the cart with the monitor to the indicated position. Each nested block began with the presentation of a sentence summarizing the instruction about the task and the direction (e.g. "Move gaze to the right until you are just no longer looked at"); the instruction for a nested block was also present during each trial, split in two parts and framing the picture stimulus. Each trial of the nested block began with the presentation of the starting picture. For the from-center movements this was a randomly chosen picture from the center (the straight gaze plus or minus two pictures in either direction). For the to-center movements this was a picture from the periphery, randomly chosen from the five most peripheral gaze directions. The gaze of the looker could be adjusted by using the *mouse wheel*. A forward movement of the wheel resulted in a gaze change to the right, while a backwards movement resulted in a change to the left. For any given trial, the movement was restricted such that only one of the two movement directions (to the right, or to the left) was possible. For instance, when the design specified "to the right", the observer could change gaze direction only in the range between the center and the most extreme horizontal right position. The observer was able to adjust the looker's gaze direction in both directions until he was satisfied with his choice. When he accepted his final choice with the enter key, the next trial began.

Results

Gaze eccentricity measurements within the nested blocks were averaged (collapsing over image mirroring and sequence reversal), resulting in 24 data points per participant per distance, 6 for each combination of 2 sides (left vs. right) and series (ascending vs. descending). Figure 2 shows the grand means of the eccentricity measurements in degrees of visual angle; negative values are for gaze to the left, positive values for gaze to the right. For the statistical analyses, all negative signs were omitted. The data were subjected to an ANOVA with the variables distance, which (159, 220, 300, 418, 575, 790 cm), side (left vs. right) and series (ascending vs. descending) revealed a main effect for series only, $F(1,14) = 7.97$, $p = .014$, $\eta_p^2 = 0.28$; the main effect for distance was just not significant, $F(5,70) = 2.33$, $p = .051$, $\eta_p^2 = 0.01$. The other effects were not significant, Fs< 1.24, ps>.30. The mean for ascending series was smaller than the mean for descending series (1.85 vs. 3.37). The small just-not-significant effect of distance reflects a slope of 0.034°/m for the eccentricity/distance regression ($R^2 = .39$).

Based on the assumption that distance influences perceptual uncertainty and that perceptual uncertainty can be measured as the variability of judgements, the variability of the participant's responses was analyzed. That is, the analysis had the same structure as before, but instead of the mean for each condition, the observer's standard deviation for each condition served as the dependent variable. The corresponding ANOVA shows a significant main effect for distance $F(5,70) = 5.13$, $p < .001$, $\eta_p^2 = 0.094$ and series, $F(1,14) = 6.65$, $p = .021$, $\eta_p^2 = 0.024$. The variability increased roughly linearly with distance (0.89, 1.01, 0.96, 1.09, 1.17, and 1.35), from the shortest to the longest distance. It was also larger for the descending than for the ascending series (1.01 vs. 1.15).

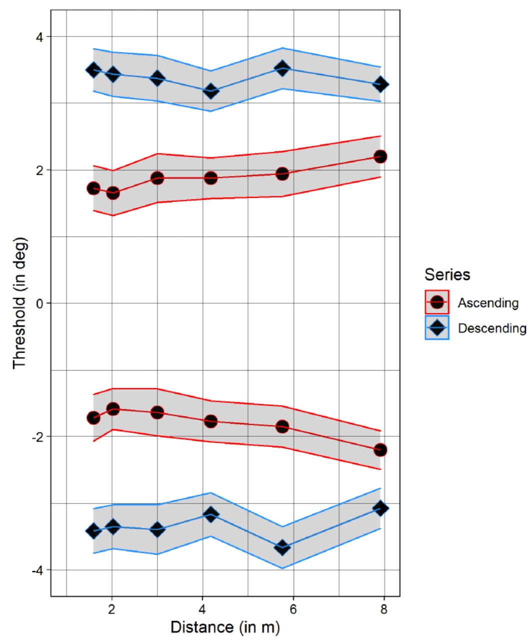

Figure 2. Average eccentricity measurements. Negative values are for gaze to the left, positive values for gaze to the right. The grey shaded areas indicate the standard error of the mean (i.e. SD/$\sqrt{N}$).

Discussion

The experiment rendered three main results. First, the visual angle of the gaze cone is quite constant in the range between 159 cm and 790 cm and symmetrical to each side. Second, the variability in the participants' answers increases with distance. Third, participants indicate somewhat different gaze-cone thresholds in ascending and descending series.

Participants are relatively constant in their averaged judgements of the threshold for direct gaze over the tested distances. Averaged over ascending and descending series, the gaze cone was 5.2° wide in diameter. The (not significant) effect of distance was small and amounted to only 2 min of arc per meter. The constancy of the cone angle is consistent with the conception of the gaze cone as defined by a particular visual angle by Gamer and Hecht (2007); in fact, the results suggest an almost perfect cone for the tested distances. Moreover, the cone shape was measured here for the first time parametrically, and thus provides additional confidence in the cone concept. In addition, the range of measuring points was somewhat extended from 1–5 m (Gamer & Hecht, 2007) to 1.6–7.9 m in the present experiment.

How can the cone's constancy be explained? For the clarity of our discussion, we distinguish between the *gaze cone* (which is the area in space that is defined by the range of gaze directions that an observer will accept as directed at him or her, cf. Balsdon & Clifford, 2018; Gamer & Hecht, 2007), and the *attributed looking area*, which is the area that the observer perceives as the region where the looker is looking at. Considering that perception is very good in the fovea but quickly deteriorates in the periphery (e.g., Irwin, 1992), it is a reasonable assumption for the observer that the looker's looking area is limited and does not include the entire visual field. Moreover, as the fovea is not a point but an area (5.5° in diameter when defined anatomically, e.g., Hendrickson, 2009), it is a reasonable assumption that the attributed looking area is also not a point but an area of some extension. Note that the looking area is defined with reference to the perceptual system of the looker, while the gaze cone is defined with reference to the judgement of the observer. Based on these considerations, it is our suggestion that the gaze cone derives from the attributed looking area, and that it is not a coincidence that the sizes of the fovea (~ 5°) and of the gaze cone (~5–10°) have similar orders of magnitude. The constancy of the gaze cone derives from the constant size of the attributed looking area, which in turn is based on the constant size of the retinal region that supports sharp and detailed vision. Note that the attributed looking area and the gaze cone correlate, but need not be the same. For example, if the observer's head is very close to the looker, the looker's head covers a large area, and the looker has to direct his gaze far to the side in order to avoid looking at the observer, even though his looking area is constant.

While the gaze cone's visual angle remains constant when distance is increased, the same is not true for the variability of judgements: The variability of judgements increases. Is this an indication that uncertainty increases with distance (Mareschal et al., 2013)? It is clear that the quality of the visual image decreases when distance is increased mainly because the retinal size of the relevant stimuli decreases while retinal resolution remains constant. Therefore, because of the observer's limited visual acuity, his or her ability to discriminate a looker's gaze directions decreases monotonically with distance. This does not necessarily result in a change in mean judgements, if uncertainty registers in random scatter around the mean. The present analysis gives evidence to this assumption and indicates that with increasing distance between looker and observer, the observer gets increasingly uncertain where the looker looks at, and the judgements are getting increasingly more variable, even within the relatively near distances ranging from 1.5 to 8 m.

Returning to the gaze cone size again, we found slightly different thresholds in ascending and descending series. These are consistent with a conservative bias: Participants are "reluctant" to change their judgement, in this case, from "She is looking at me" to "She is no longer looking at me", and from "She is no longer looking at me" to "She is looking at me". A symmetrical bias such as the conservative bias can be eliminated by averaging results from the ascending and descending series, as the bias cancels out. According to this view, the average of the ascending and the descending series is the best guess for the real cone size.

In addition to the difference in thresholds between ascending and descending series, we also found a difference in variability. This would be consistent with the assumption that there are different levels of uncertainty in ascending and descending series. In particular, the ascending series seem to cause more uncertainty than the descending series. A possible explanation for this pattern is that the descending series start from a highly salient gaze direction, which is straight gaze. There are multiple cues to straight gaze: (a) the mirror symmetry of the lateral (outer) parts of the sclera of both eyes, (b) the mirror symmetry of the nasal (inner) parts of the sclera of both eyes, and (c) and the perfect circular shape of iris and pupil. The highly salient straight gaze provides a much better anchor and implicit distance measure than the averted gaze which is the starting point in the ascending series. In considering the larger variance for the ascending series, one might suspect a mere statistical artefact, as the ascending series have a higher mean than the descending series, and higher means tend to be associated with higher variances. This is not convincing, though, because the assignment of numbers to rotation angles is rather arbitrary.

Our experiment might be criticized on the grounds that while distance was varied, the stimuli were the same for all distances and thus, the looker's vergence was fixed. We would like to yield two perspectives on this critique. The first perspective is that while this study might thus not scale to natural interactions where the looker's vergence adapts to the distance, it is nonetheless representative for the ubiquitous situation, where reproductions of lookers (with necessarily fixed vergence) are presented to the observer through the diverse media. The second perspective is as follows. The looker's fixation distance was chosen to be at the observer's threshold for vergence perception. As we know of no empirical data on the thresholds of vergence perception, we used normal (Snellen 20/20) acuity of 1 min of the arc as a default. Of course, the just noticeable pupil displacement depends on distance for a given visual acuity. Accordingly, the minimal eye rotation that can be perceived increases with distance. At the same time, the looker's vergence gets smaller when distance is increased (see Appendix A for details). The two curves cross at 164 cm. In other words, at distances of 164 cm and above, the small residual vergences cannot be discriminated from each other. We thus assumed that the looker's vergence in our experiment was already barley perceivable at the shortest distance, and that the small changes in vergence that would be present in a real looker for the examined distances were all not discriminable from the distance presented. We therefore argue that the results hold for natural situations with real lookers as well.

The size of the gaze cone measured in the present experiment is smaller than reported in some other published studies (e.g., Hecht et al., 2015; Balsdon & Clifford, 2018; Gamer & Hecht, Exp. 1–3; Jun et al., 2013; Otsuka et al., 2014), although not in all: For example, Gibson and Pick (1963) found a threshold of 2.8°, corresponding to a cone size of 5.6° (see also Gamer & Hecht's Exp. 4, that found a gaze cone of 3.9° at a distance of 5 m). We may provide two views on this observation. The first view is that not all variables of cone size are known, such that there probably is no "real" cone size. There is evidence for cone size influences on the side of the observer: Jun et al. (2013), for instance, found a larger cone size for men with social anxiety. Moreover, it would be surprising if the stimulus – the looker – has no effect. For instance, Anstis et al. (1969) found the overestimation effect to be reduced if more of the eyeball is visible (note that this was for an artificial eye and that it has yet to be confirmed whether this influence also applies to a human eye). A larger overestimation effect in a given eye stimulus would lead to a narrower gaze cone, because the subjective threshold for directed gaze is reached by less extreme objective eye rotations. Unfortunately, an objective measure of eye size has yet to be defined. Our subjective impression, however, is that the visible eye in our stimulus is quite large, rendering the overestimation account of the cone size unconvincing. Also, our looker model had brown eyes with little contrast between pupil and iris. It has been hypothesized that a reduced perceptibility of gaze results in a wider cone (Mareschal et al., 2014). Thus, it is possible that the gaze cone is small here because of the good perceptibility of the eyes. Finally, the obtained cone size might be influenced by the method of measurement, as we have seen here, where already the use of ascending and descending series resulted in subtle differences in cone size.

The second view is that the present results are credible for the tested viewing distances. Viewing distances of 160 cm and more have rarely been tested, and were they have been, cone sizes seem to be more in the range of 5–7° (e.g. 6.4°, at 5 m on average in Gamer & Hecht, 2007, and 5.6° at 2 m in Gibson & Pick, 1963).

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Appendix A

For the sake of simplicity of presentation, it is assumed that the looker and the observer stand exactly in front of each other at varying distances, and that the looker looks to the observers left eye. Thus the looker-fixation point distance and the looker-observer distance are the same and can be handled by one distance variable. The looker's vergence is given by (1):

(1) vergence = arctangent (6.5/distance)

where 6.5 is the distance of the eyes in cm. The observer's threshold is given by (2):

(2) displacement threshold = distance*tangent (1/60)

where 1/60 is normal acuity (Snellen 20/20)

However, to be useful, we need the threshold for eye rotations, which is given by (3):

(3) rotation threshold = arcsines (displacement threshold /1.2)

where 1.2 is the eyeball radius.

The difference between vergence and rotation threshold is zero at a distance of 164 cm. Moreover, the small vergence of 2.28° is below the threshold for larger distances.