Article

PERCEPTION

How vergence influences the perception of being looked at

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Linda Linke and Gernot Horstmann
Bielefeld University, Germany

Abstract
Perceiving other people's direct gaze is important for many areas of everyday activity. For horizontal and vertical eye movements, the area of being looked at, known as the cone of gaze, has been well explored. Previous research has shown a range of eye rotations (up to eccentricities of 4°–9°) that people accept as direct gaze. Vergence is an important cue for perceiving the depth of fixation. This study examines the range of vergence angles that support the perception of being looked at. In two experiments, observers adjusted the degree of vergence of the lookers' eyes until they felt just (not) looked at. The first experiment also asked to adjust the point of being exactly looked at, which was 0° (parallel eyes). The thresholds of being just (not) looked at were around 4.5° of convergence and 2.5° divergence, which results in a depth of 7° of vergence. This depth was replicated in Experiment 2, while the thresholds of convergence (3.5°) and divergence (3.5°) slightly differ from Experiment 1. The results indicate a consistent area of vergences being accepted as direct gaze, yielding first-time evidence for a third dimension—the depth dimension—of direct gaze.

Keywords
direct gaze, gaze cone, vergence, visual perception

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Perceiving direct gaze has a strong impact on behavior. When people feel being looked at, they tend to exhibit more socially desirable behavior and less undesirable behavior (Dear et al., 2019). A direct gaze leads to more self-awareness (Baltazar et al., 2014) and enhances mental-state attributions (Pönkänen et al., 2011). Furthermore, the direction of gaze gives insights into the intentions and the objects of attention of the looking person (Baron-Cohen, 1997; Cline, 1967). In particular, the human eye with its light sclera and the dark pupil offers a good impression of someone's looking direction (Kobayashi & Kohshima, 1997, 2001).

When do people perceive direct gaze? Direct gaze seems to be an area (rather than a point), which can be defined by the range of eye rotations that people perceive as being directed at

Corresponding author:
Linda Linke, Department of Psychology, Bielefeld University, Bielefeld, Germany.
Email: linda.linke@uni-bielefeld.de

them, also known as the cone of gaze. Gamer and Hecht (2007) described the gaze cone as an area with a constant angle, which remains stable over distance. These researchers asked participants to adjust the gaze of a looker model until the gaze of the looker is no longer directed at them. They tested two distances (1m and 5m) and found a stable cone in the range between 5°–10° (Horstmann & Linke found a 5° wide stable cone). The results of Horstmann and Linke recently confirmed the stability of the cone angle over distance by using an extended range of distances for a portrait of a looker model (from 1.6 m to 7.9 m). The gaze cone has been investigated for horizontal and vertical eye directions (Gamer & Hecht, 2007; Mareschal et al., 2013; and van Eijk et al., 2010).

Despite these convincing results for the gaze cone model, it remains unclear how the depth of fixation (or fixation distance) influences the cone. If the looker fixates on some object nearby, his eyes converge, that is, they are rotated into the direction of each other. If he looks to objects far away, the eyes are roughly parallel. In some forms of strabismus (e.g., exotropia), one or both eyes is/are turned outward, and the eyes diverge. The angle between the eyes that is related to the fixation distance is called vergence (see Figure 1). The vergence angle is defined as the angle between the optical axes of both eyes in the horizontal plane (Mays, 2009). While it is known that vergence is an enteroceptive cue in distance perception (Tresilian et al., 1999), there is little research directly relating to the question of how vergence is perceived, and how good it is used to infer the fixation distance of a looker. Despite this scarcity of evidence, it seems to be a reasonable assumption that the vergence of another person's eyes can be perceived and used to infer the fixation distance. If people are aware of another person's depth of fixation, they should in turn be able to perceive whether a person is looking behind, or in front, or directly at them.

Consider the following example:

You are standing at the end of a waiting queue to buy some ice cream. A person near the top of the queue turns around, looks into your direction and starts to wave, and you greet them back. However, then, doubts arise: Is this waving as well as this gaze actually directed at you? Or is it directed at a person standing in front of you? Or, perhaps, at another person standing behind you? Multiple possible recipients stand right behind each other, they are only slightly horizontally offset from each other so that they are all visible to the looker. Each one of them could be addressed by a similar horizontal gaze direction of the looker, which would be hardly distinguishable from each other only by horizontal gaze direction. In this situation, the looker's gaze can be directed to different observers who must distinguish by the vergence of the looker's eyes if they are addressed by his gaze, or if the person in front or behind them in the queue was meant to be addressed by the looker's gaze. To summarize, when all possible recipients stand in the same line of gaze, the depth of the fixation plays an important role, and the only possible cue is the vergence of the eyes.

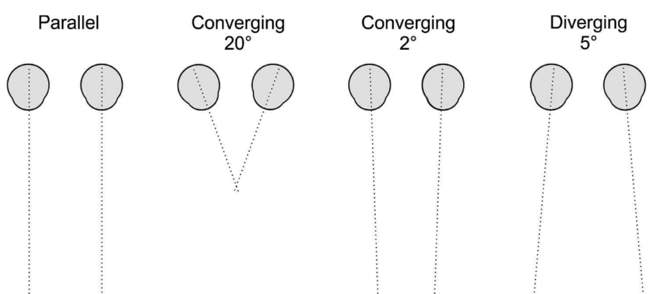

Figure 1. Examples for parallel eyes (left), two angles of convergence, with fixation points at different distances, and divergence.

Everyday observation suggests that we can easily distinguish between a person who is fixating on an object a few centimeters away, and a person who is fixating on an object 25 meters away; however, the accuracy of this judgment remains unclear. Nguyen et al. (2018) found a bias when judging the distance on the basis of perceived vergence. They asked their subjects to indicate that distance which is implied through a specific vergence angle. Similar to the overestimation bias (Anstis et al., 1969) in horizontal conjugate eye movements, there is the tendency to overestimate the looker's vergence. This means that people tend to perceive divergent gaze as parallel gaze, while perceiving parallel gaze as convergent gaze, and perceiving convergent gaze as even more convergent (Nguyen et al., 2018).

Honma (2013) made a first approach to study vergence in its relation to the perception of eye contact. He randomly assigned participants as the looker or the observer. They sat 114 cm apart from each other. In half of the trials, the looker was instructed to either look on an index-pole tip, which was placed between looker and observer, and which randomly varies in the position in the horizontal (x-axis), vertical (y-axis) as well as in the depth dimension (z-axis). In the other half of the trials, the looker was instructed to fixate a point between the observer's eyes. The observer had to judge if he has made eye contact with the looker. Although Honma (2013) did not report a range of vergence angles in which the observer felt being looked at, it can be inferred from the description of his results, that observers perceived eye contact even when the looker was fixating a point 82 cm in front of them. This would correspond to a vergence angle of 5.7°, whereas the natural vergence angle would be only 1.6°. Unfortunately, Honma's main interest was not the direct gaze itself but other factors, so there is no exact statement of the thresholds of the perception of being looked at. Nevertheless, the range of distances in which observers perceived eye contact was large.

The relatively wide acceptance of direct gaze in the study by Honma, and the bias in the perception of vergence, which can be seen in the study of Nguyen et al. (2018), may be traced back to angle kappa. Kappa results from the misplacement between fovea and pupil and is a measure for the difference between visual/foveal axis and pupillary axis. Kappa can be measured by the reflection of the light on the cornea, when a person looks directly at a lamp held by the examiner (Scott & Mash, 1973). The location of the light reflection gives information on the degree of displacement. If the light is centered in the middle of the pupil, angle kappa is equal zero, which means, fovea and pupil are perfectly aligned: The visual axis and the pupillary axis are the same. Positive kappa angle values refer to a nasally displaced light reflection, while negative angles refer to a temporally displaced light reflection. The visible vergence angle is the sum of the vergence angle that is necessary to visually fixate on the object, and angle kappa. Different kappa values could lead to different visible vergences and may be one reason for a considerable tolerance of vergence angles in the context of direct gaze, as well as the difficulty of precise estimation of distance on the basis of perceived vergence. Furthermore, West (2010) have found evidence for the influence of angle kappa in the estimation of horizontal gaze; there is thus good reason to expect that kappa could play a role in vergence perception as well.

In the current study, we examined the influence of vergence on the perception of being looked at. Similar to horizontal and vertical eye movements, where a range of rotation angles gives rise to the perception of being looked at versus not being looked at, we assumed that there is a corresponding range of vergence angles that support direct gaze. Thus, we asked subjects to adjust the vergence of a straight looking virtual looker. To determine the borders of a possible area, we used converging and diverging gaze. Converging gaze was used to establish the thresholds of direct gaze in front of the subject (proximal border), while the diverging gaze was used to find the threshold of direct gaze behind the subject (distal border). In addition, we investigated at which point participants felt exactly looked at, i.e., the perceived central depth of gaze, to relate our results to the overestimation effect by Nguyen and colleagues. Thus, our aim was to find the proximal and the distal border, and the perceived central depth of the perception of being looked at.

Experiment 1

Method

Participants. Twelve observers (4 male, 8 female) aged between 17 and 30 years volunteered for course credit or candy. The sample size was chosen on the assumption of a large effect size, which can be observed in the gaze-cone research on horizontal and vertical eye movements. All observers had normal or corrected visual acuity and intact color vision. They gave written informed consent before participation. The experiment was approved by Bielefeld University's ethic committee.

Apparatus and Stimuli. A computer-generated avatar was presented on a 36.4 cm × 27.7 cm sized Sony Multiscan G420 monitor with a frame rate of 89 Hz. The display had a resolution of 1.280*1.024 Pixels. The stimuli were presented in full screen mode. The width of the head was 16.5 cm and the height 25.8 cm. Its interpupillary distance was 6.5 cm. The screen size of the virtual head approximately equalled that of an adult human head at screen distance. The virtual head was generated by a modified Sims (Die Sims™ 4, Electronic Arts GmbH) avatar, in which both eyes were cut out and replaced by transparent pixels. The simulated eyes were created and controlled by a custom written Python script as simulated spheres. The relative sizes of the eyeball, iris, and pupil were based on normative data such that the iris was 30% of the eyeball size, and the pupil was 10% of the eyeball size (Gharaee et al., 2014; Sanchis-Gimeno et al., 2012).

Eyes can be controlled independently in their horizontal rotation. Furthermore, it is possible to adjust the vergence angle between the eyes. The avatar mask, with removed eyes, was laid over the simulated eyes. For this experiment, the horizontal eye position was fixed to 0°. If the eyes are perfectly parallel and oriented perfectly straight (rotated by 0°), vergence is 0°. In the case of convergence, the eyes are both symmetrically turned to the center, which is indicated in the following by a positive vergence angle. In the case of divergence, the eyes are symmetrically turned to the side, which is indicated as negative vergence. The vergence angle as defined as the angle between the optical axis between both eyes could be varied between 20° converged eyes and – 12° diverged eyes, or accordingly rotations between 10° and – 6° for a single eye (see Figure 2). In the following, the vergence angle will always be reported as the single eye rotation. The observer sat 90 cm in front of the monitor, for which the natural vergence of the looker would be 2° for each eye. In this distance, it is possible to adjust the vergence angle to a relatively high degree of convergence for a possible proximal border. Convergence of 10° reflect a fixation distance of 72 cm in front of the observer. Nevertheless, 90 cm also allow a range of vergence angles between 2° and the parallel

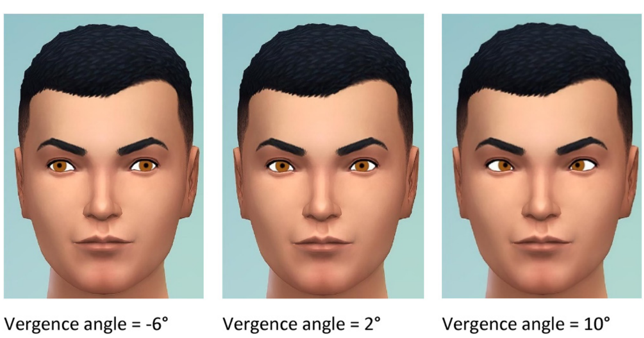

Figure 2. Examples of the presented stimuli with different vergence angles.

eyes for the distal border. A convergence of 0.5° would reflect a fixation distance of 282 cm behind the observer. Parallel eyes as well as diverging eyes cannot be assigned to a specific distance but reflect a fixation above 4 meters to infinity. The height of the observer's eyes was fixed on the plane of the avatars eyes height by using a chin rest.

Design and Procedure. The experiment consisted of two blocks. Each of the two blocks referred to a specific mode. In the first block, borders of direct gaze should be detected (mode = border). In the border mode, observers were asked to adjust the gaze until they just felt looked at, or adjust the gaze until they no longer felt looked at to determine proximal and distal cone border. In the second block (mode = central depth), observers should adjust the gaze until they exactly felt looked at to determine the perceived central depth of gaze.

In the border mode, the series factor of pictures that were shown was varied. There were ascending series and descending series. Ascending series started with an extreme vergence (either maximum convergent or divergent eyes) and could be adjusted in direction of natural vergence angle, which is 2° at 90 cm distance between looker and observer. Descending series started with natural vergence angle and could be adjusted to 10° convergent or – 6° divergent eyes. The combination of the factors led to two conditions for converging eyes and two conditions for diverging eyes. In the central depth mode, only ascending series were used, but with the possibility to adjust the gaze from – 6° diverged to 10° converged and vice versa.

Border mode reveals four possible conditions, two for converging eyes and two for diverging eyes. The first condition for convergent eye series combined the instruction "just looked at" with using ascending series that started with eyes converged to 10° for each eye. The participants then adjusted vergence in steps of 0.5° for each eye until that point where they perceived gaze as just directed at them. The maximum possible value—the reference point—was vergence angle of 2° for each eye, which is the natural vergence angle in 90 cm distance. The second condition for convergent eye series combined the instruction "no longer looked at" with descending series with eyes starting at natural vergence angle (vergence = 2°); vergence could be adjusted in steps of 0.5° to a maximum of 10° convergence per each eye. The same procedure was used for divergent eyes, but in contrast to the convergent eyes, the divergent eyes were labeled with negative vergence values. The first condition of divergent eyes series combined the instruction "just looked at" with ascending series, starting with eyes diverged to – 6° and could be adjusted in steps of 1° until the eyes were converged to natural vergence angle (vergence = 2°). The second condition for divergent eyes combined the instruction "no longer looked at" and the use of descending series, starting with natural vergence angle (vergence = 2°) and could be adjusted to – 6° diverged eyes. In the mode of central depth in ascending series, eyes either start 10° converged and could be adjusted in steps of 0.5° to – 6° diverged, or the other way round. In contrast to the border mode, observers are instructed to adjust eyes until they felt exactly looked at.

Presentation and response registration were controlled by a custom written Python script using routines from PsychoPy (Peirce, 2008). The instruction for a given trial was presented before each trial and was seen in a shortened version while performing the task. The adjustment of the eyes was made by using the scroll wheel of the mouse. By scrolling upward, the gaze was shifted into the direction of the nose (into the direction of more convergence), while scrolling downward leads to a shift to the outer edges of the eyes (into the direction of more divergence). The observers could adjust the eyes as long as they wanted to; they confirmed their final result by pressing the "enter" key on the keyboard. Two warm-up trials were made before the experiment proper, during which the researcher probed the participants' understanding of the task and provided answers to possible questions.

The conditions were presented fully randomized, and each combination was repeated 8 times resulting in 32 trials for block one, and 16 trials for block two plus 2 practice trials per observer.

Results

The data of all 12 observers (n = 12) could be analyzed. First data were split by mode ("border" vs. "central depth"). In the border mode, the new factor side is created by labeling ascending and descending series of converging eyes as the proximal border condition, and ascending and descending series of diverging eyes as the distal border condition. In the next step, the data were aggregated by observer, series, and side, which resulted in one mean per observer for all factor levels of side ("proximal" and "distal") as well as series ("ascending" and "descending"). Aggregated data were subjected to a repeated measure ANOVA with the within variables series ("ascending" vs. "descending") and side (proximal vs. distal), and the between variable of the observers revealed a main effect for side $F(1, 11) = 166.01$, $p < 0.01$, $\eta^2_G = 0.89$, and series $F(1, 11) = 7.03$, $p = 0.02$, $\eta^2_G = 0.01$, and a significant interaction of series and side $F(1, 11) = 19.18$, $p < 0.01$, $\eta^2_G = 0.31$.

The mean vergence for descending series (proximal border: 5.71°, distal border: – 3.31°) was more extreme (i.e., the absolute was larger) than for ascending series (proximal border: 3.72°, distal border: – 1.81°). By collapsing over the series factor for each side, the possible hysteresis bias reflected in the effect of series was eliminated. The mean for the proximal border is 4.70°, and – 2.56° for the distal border (see Figure 3). We tested whether the mean vergence angle of the proximal border differs from natural vergence angle at 90 cm, which is 2.07°. *T*-test reveals a significant difference $t(23) = 7.56$, $p < 0.01$, $d = 1.54$. The same was repeated for the distal border, where the *t*-test was also significant, $t(23) = -15.285$, $p < 0.01$, $d = -3.12$.

Overall, it can be observed that 80% of vergences in the proximal border condition were chosen to be between 2° to 7°, with only 11% were chosen to be the exact natural vergence of 2°. Only in 0.01% of the trials the eyes were converged to the maximum of 10°. Diverging eyes seem to be judged a little different: In 80% of the trials, angles were chosen to be between – 1° to – 9°, with only 0.01% usage of the natural vergence angle and again a quite small usage of the maximum of divergence with 5%.

For the mode of perceived central depth, the series of 10° converged to – 6° diverged and – 6° diverged to 10° converged were averaged for grand mean of central depth. The vergence angle,

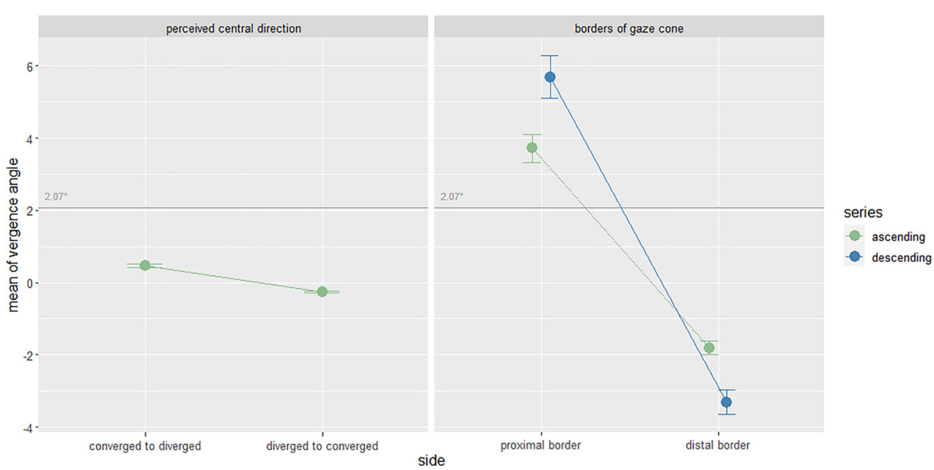

Figure 3. Average vergence measures in degree. Negative values refer to divergent eyes and the distal border. Positive values refer to convergent eyes and the proximal border. In the perceived central depth with ascending series, eyes either start 10° converged and could be adjusted to – 6° diverged, or the other way round. Error bars describe the standard error of mean vergence angle. The gray line visualizes the natural vergence at 90 cm distance.

where observers felt exactly looked at, was at 0.10° of vergence for each eye (see Figure 3). *T*-test against natural vergence angle reveals a significant difference between natural vergence angle and the perceived central depth, $t(21) = -8.61$, $p < 0.01$, $d = -1.76$.

Discussion

Concerning the influence of vergence on the perception of direct gaze, very little data are available. The current study is a first approach to close this research gap. The analysis rendered three main results. First, there is an influence of vergence on the perception of being looked at: Some vergence angles are not accepted by the observer to be directed at him. Second, there is not a single vergence angle that is accepted as direct, but rather a considerable range of vergence angles. Third, the overestimation effect for vergence reported by Nguyen et al. (2018) is mirrored in the results of perceived central depth of direct gaze.

The data clearly show that a range of vergence angles support the perception of being looked at, and this range is not small. It comprises an area with a relatively large elongation of 7° of vergence per eye, wherein any vergence is accepted by the observers as being direct. In particular, the area extends between 4.5° (proximal border) and − 2.5° (distal border) of vergence angles per eye. The proximal border corresponds to a fixation 50 cm in front of the observer, while distal cone border seems to extend until infinity. Because parallel eyes cannot be assigned to a specific distance, and diverging eyes are extending even more, no endpoint of the area of direct gaze can be measured. This implies that the area of being looked at could be shaped like a comet with a tail (see Figure 4). Furthermore, our results show evidence for a proximal border of direct gaze which extend to 4.5° of convergence for each eye. This yields again strong evidence for the hypothesis that vergence adds a third plane—the depth plane—to the area of direct gaze.

Our analysis found a main effect of series, and an interaction between side and series can be seen. In descending series, a greater depth of the area was observed than in ascending series. This result is conceptually similar to previous studies and may be explained by an anchor effect or by some kind of conservative bias (Horstmann & Linke, 2021). The bias can be accounted for by averaging over ascending and descending series.

The third main result shows that the point where observers felt exactly looked at is not the natural vergence angle. Almost perfectly parallel eyes (0.10°, a vergence corresponding to a fixation point at a distance of 18.52 m) are perceived as being exactly directed at the observer. In other words, observers did not prefer converged eyes (2°), but chose a vergence angle which correspond to a very far distance instead of a close distance of 90 cm. This result has similarities to the overestimation effect by Nguyen et al. (2018), where observers also showed the tendency to judge parallel eyes (corresponding to distances far away) as being convergent (corresponding to distances much more nearby). We will return to this point in the General Discussion.

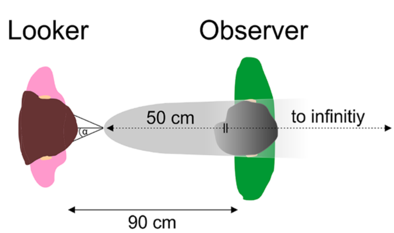

Figure 4. The concept of the area that is defined by the vergence angles that support direct gaze. $\alpha = 4.5$ ° is the convergence of the proximal border. Distal border (− 3°) could not be reflected to any distance.

Experiment 2

The overestimation bias by Nguyen and colleagues, which was mirrored in the results of perceived central depth leads to a possible problem: Converged eyes are apparently perceived as being even more converged than they are, parallel eyes are perceived as being slightly converged, and slightly divergent eyes are perceived as being straight. When we present the natural vergence of 2° as a reference point, we had expected that people perceived direct gaze exactly at this point. Our results of perceived central depth, however, show that observers have the perception of being exactly looked at with almost parallel eyes (0° vergence). When starting at the natural vergence point of 2° in some conditions of Experiment 1, it is possible that people overestimate the vergence angle and perceive the looker as fixating a point in front of them. Experiment 2 eliminates this problem by using perceived central depth as indicated by Experiment 1—parallel eyes—instead of natural vergence as the reference point, and check if the area of being looked at would be sized the same.

Method

Participants. Twenty-three observers (12 male, 11 female) aged between 18 and 32 years volunteered for course credit or candy. All observers had normal or corrected visual acuity and intact color vision. They gave written informed consent before participation. The experiment was approved by Bielefeld University's ethic committee.

Apparatus and Stimuli. The apparatus in the present experiment was identical to Experiment 1. The stimuli were similar and only differed in the reference point which was set to zero degree instead of natural vergence angle of 2°. The vergence angle between the eyes could be adjusted as described in Experiment 1, and varied between 7° converged eyes and – 7° diverted eyes.

Design and Procedure. The design was similar to Experiment 1, but only the cone borders and not the perceived central depth were measured this time. Furthermore, the reference point changes to zero degree which reveals in the following set up:

The first condition for convergent eye series combined the instruction "just looked at" by using ascending series that started with eyes converged to 7°. The participants then adjust vergence in steps of 0.5° until that point, where they perceived gaze as just directed at them. The maximum possible value was zero vergence. The second condition for convergent eye series combined the instruction "no longer looked at" with descending series with eyes starting in parallel (vergence = 0°); vergence could be adjusted in steps of 0.5° to a maximum of 7° convergence. The same procedure was used for divergent eyes, but in contrast to the convergent eyes, the divergent eyes were labeled with negative vergence values. The first condition of divergent eyes series combined the instruction "just looked at" with ascending series, starting with eyes diverged to – 7° and could be adjusted in steps of 0.5° until the eyes were no longer diverged (vergence = 0°). The second condition for divergent eyes combined the instruction "no longer looked at" and the use of descending series, starting with parallel eyes (vergence = 0°), and could be adjusted to – 7° diverged eyes.

The conditions were presented fully randomized, and each combination was repeated 15 times resulting in 60 trials plus 2 practice trials per observer.

Results and Discussion

The data of 22 observers ($n = 22$) could be analyzed. One participant was lost because of a computer problem during saving and the resulting loss of data. First, the four combinations were aggregated to the new factor side consisting of the stage proximal and distal border. In the next step, the data were aggregated using observer, series, and side as factors. For each factor combination there was only one mean per observer left. The data were subjected to an ANOVA with the variables series (ascending vs. descending) and side (proximal vs. distal), which revealed a main effect for side, $F(1, 21) = 236.43$, $p < 0.01$, $\eta^2_G = 0.86$, and a significant interaction of series and side $F(1, 21) = 22.52$, $p < 0.01$, $\eta^2_G = 0.25$. The main effect for series was not significant, $F(1,21) = 1.07$, $p = 0.31$. Figure 5 shows the grand means of vergence in degree for the factors series and side.

Again, the mean vergence for descending series (proximal border: 4.26°, distal border: −4.26°) was more extreme than for ascending series (proximal border: 2.64°, distal border: −2.77°). As in Experiment 1, we averaged both series for further analysis. The grand means for the proximal and distal borders is 3.46°, and −3.53°, respectively. We tested if mean vergence angle of proximal border differs from natural vergence angle at 90 cm (2°). *T*-test reveals a significant effect for the proximal border, $t(21) = 5.02$, $p < 0.01$, $d = 1.07$, and for the distal border as well, $t(21) = -26.10$, $p < 0.01$, $d = -5.57$. Additionally, we tested if proximal and distal border were different from the perceived central depth suggested by Experiment 1, which was equal to zero. *T*-test revealed a significant difference from zero for proximal border $t(21) = 12.62$, $p < 0.01$, $d = 2.70$, as well as for distal border $t(21) = 16.43$, $p < 0.01$, $d = -3.50$.

The second experiment reveals results similar to our first experiment. People felt looked at in an area of 7°. The proximal border extends to 3.5° of convergence, while the distal border extends to 3.5° of divergence. As in Experiment 1, converging eyes are accepted as direct, which was expected, but a surprisingly large range of diverging eyes are accepted as well. The natural vergence at 90 cm (2°) is included the depth plane of perceived direct gaze. It can be seen that again observers are willing to accept a quite large area as being direct gaze.

General Discussion

Previous research on the gaze cone had focused on conjugate eye movements to the left or to the right on the coronal (frontal) plane of the perceiver (Balsdon & Clifford, 2018; Gamer & Hecht, 2007). The gaze cone is conceived of as the range of eye rotations that are accepted as being

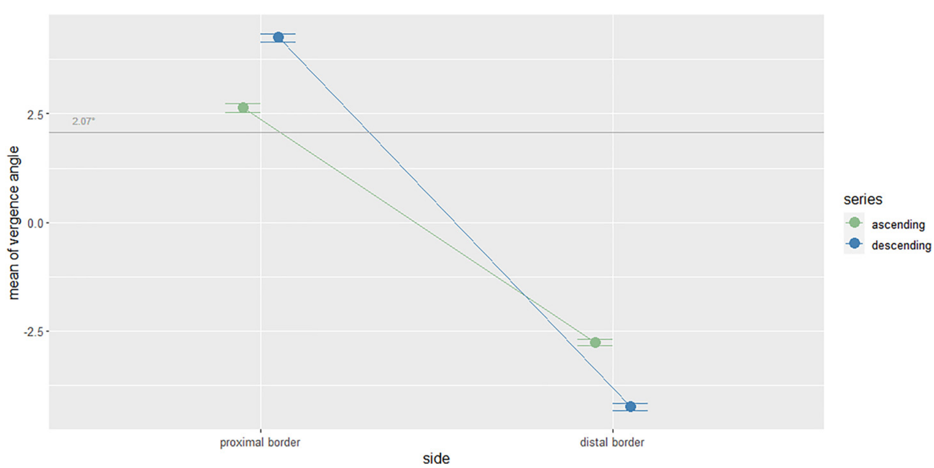

Figure 5. Average vergence measures in degree. Negative values refer to divergent eyes and the distal border behind the observer. Positive values refer to convergent eyes and the proximal border in front of the observer. Error bars describe the standard error of mean vergence angle.

direct, resulting in a model of a cone that is characterized by a constant angle and originates between the eyes of the looker. Vergence eye movements were controlled as well to adjust vergence to the looker–observer distance. Horizontal eye movements that had been the target of most research, however, do not exhaust the possibilities. Conjugate eye movements, where the eyes are rotated by the same angle, can be vertical in addition to horizontal when the eyes fixated on points in the frontal plane. In addition, vergence eye movements fixate the eyes on points at different depth, that is in the sagittal plane. Although the integration of the depth dimension in the gaze cone concept is somewhat challenging, vergence eye rotations cannot be ignored. The results of the present experiments support the assumption of a third dimension—the depth dimension—for the gaze cone. The aim of the study was to test the hypothesis of an area of perceived direct gaze in depth, as indicated by a range of vergence angles that are accepted as direct. In two experiments, an area of 7° (Exp. 1 & Exp. 2) emerged in which people perceived being looked at.

One might ask why the observers were allowed to adjust eyes up to divergence. A more technical reason is that without diverging eyes, adjustment for the distal border would have to start at a positive angle (e.g., 2°, the natural vergence, see above) and would have to be adjusted into the direction of a lower vergence angle in steps of 0.5° up to no vergence (0°, parallel eyes). The adjustable range would have been very narrow, and the objectively parallel eyes might not necessarily correspond to the perception of a looker that looks "through" the observer. In addition, the relation between distance and vergences follows an exponential function. In near distances (like 60 cm), changes of a few cm result in large differences in vergence, while in distances slightly farther away (like 160 cm), the same change of a few cm is mirrored in a very small change in visible vergence. In fact, because of the limited visual acuity of humans, changes in vergence angles above 165 cm of distance are barely perceivable for observers (for further information see Horstmann and Linke, 2021). Because of this characteristic of the distance-vergence function, and because of the fact that there is evidence that parallel gaze is perceived as convergent and diverged gaze is perceived as parallel due to the overestimation effect (Nguyen et al., 2018), it is a logical conclusion that observers should be allowed to also choose diverging eyes. Furthermore, slightly diverging eyes can be the result of the deviation of the optical axis to the foveal axis. This deviation is conventionally measured as angle kappa. According to Basmak et al. (2007), angle kappa is positive for the majority of the population, where the fovea is temporally displaced, that is, in the direction of the side of the head. A positive angle kappa has the effect that the rotation of the eyes toward each other (vergence) for any fixation distance is smaller than when angle kappa is 0°. Of course, this also implies that the fixation on an object far away would not lead to parallel, but slightly diverged eyes (for more information see West, 2013). Although highly diverging eyes are an unnatural stimulus, which cannot be observed often in daily life, they were frequently selected by the observers in the present study. In fact, our observers preferred slightly diverging eyes as well as parallel eyes above natural vergence angle of 2° when they had to adjust the distal border of direct gaze.

Nguyen et al. (2018) found an overestimation of vergence as indicated by an underestimation of distance: Straight gaze was apparently perceived as slightly converged, and convergent gaze was seen as more extreme as it actually is. The present results are consistent with this convergence effect. In particular, the overestimation hypothesis by Nguyen and colleagues is supported by the results of central depth in Experiment 1. Although natural vergence angle would be 2° for each eye in 90 cm (which was the viewing distance in both experiments), observers instead chose 0° vergence as the point where they felt exactly looked at. This fits to the result of Nguyen and colleagues that true parallel eyes are perceived as being convergent. A different explanation would be an overall difficulty in estimating gaze direction through vergence. This seems a little implausible when thinking of the accuracy within people's triadic judgments of gaze direction, which show very good sensitivity to eyeball rotations with about 1° of eyeball rotation for a distance of 1 m (Symons, Lee, Cedrone, & Nishimura, 2004).

Our results on the depth dimension of the area of direct gaze reveal a number of theoretical implications. Consider the following example: In social media like Instagram, users often film themselves, some with their smartphone held at arm's length (about 40 cm), some at usual smartphone-viewing distance (about 25 cm), and some with a monitor mounted camera from their notebook or desktop computer (e.g., 75 cm). Viewing distance, on the other hand, may vary from short distances for a smartphone held near the face (e.g., 25 cm) to clearly longer distances for a desktop computer (e.g., 75 cm). Thinking about a social media user/influencer (our looker in this case) being photographed in 25 cm distance who is gazing directly into the camera. The convergence angle of each eye would be 7.5°. A follower (an observer) may watch the user's post on his smartphone in 40 cm distance, for which a vergence angle of 4.6° would be adequate, or on his desktop monitor in 75 cm distance, for which a vergence angle of 2.5° would be fitting. In both cases there is a clear difference between viewing distance and recording distance, and accordingly, the corresponding vergence angles. The results of the first Experiment show that convergence is accepted as direct almost up to 5°. The natural vergence angle in the first Experiment, which corresponded to a 90 cm looker-observer distance, would have been 2°. It follows that at the proximal border, vergences supporting direct gaze are allowed to be 3° more converged than the natural vergence. Resuming the social media example: Recording distance of the stimulus was 25 cm, which corresponded to a vergence angle of 7.5°. According to the 3° rule, any convergence between 7.5° and 4.5° should be acceptable as direct gaze. Because convergence at 75 cm consuming distance is 2.5° and at 40 cm distance is 4.6°, we could possibly expect a rejection of the gaze to be direct in 75 cm, but not at 40 cm consuming distance. In contrast, in everyday social media use there is little mentioning of the possibility that the perception of direct gaze changes with distance.

One might argue that the projected head is not perceived to be at the same distance as the display screen. In other words, when looking at pictures, the default assumption might be that the looker is looking straight into the camera, and different vergences are perceived as different distances between the looker and the observers. This points to the old problem of picture perception: Where is the object in the implied picture space? When only one object is presented as in the present experiment, the observer may be relatively free to assume a distance ad lib, and he may use vergence as a cue to distance. This is an important caveat for the interpretation of the results, and should finally be tackled by an experiment with an embodied ("live") looker, where the observer-looker distance is not ambiguous. However, this argument has a rather implausible implication. As the present experiment uses the method of adjustments, it implies that the pictures would advance or recede perceptually, for converging and diverging eye movements, respectively. This is, however, not the impression during a trial, and has never been mentioned by the participants. Rather, the distance of the face does not perceptually change. Very probably, the constant size of the face was used as a strong cue for constant distance. While the ambiguous distance of an object in the implied picture space is a complication for the perception of vergence in 2D renderings of faces, it probably played no role in the present experiment.

It is tempting to reverse the social media example from above and postulate that it is just because of the varying stimulus from self-recorded images in social media that we have learned that a wide range of vergence angles is indicative of the looking person looking straight at the camera, and by implication, straight at the observer. However, the perception of direct gaze is fundamental to humans who begin life with little communicative skills but the propensity to look into other people's eyes (in particular, the eyes of the care giver, Farroni et al., 2002). Given the fundamentality of direct gaze detection, and the lifelong expertise, it seems not that likely that a few years of familiarity with social media leads to such a strong distortion of gaze perception.

Another explanation can be derived by considering angle kappa. In the ideal world, the pupil and fovea are placed exactly in line, and the vergence angle can be computed exactly by knowledge of the interpupillary distance and fixation point distance by using trigonometry. Unfortunately, angle kappa varies in healthy subjects (Basmak et al., 2007), with most studies tend to find a positive average of angle kappa (Barry et al., 1992; Basmak et al., 2007). This leads to two assumptions: First, when different people fixate on an object in the same distance, different angle kappas lead to different visible vergence angles. In this case it is very useful to accept multiple vergence angles as being looked at, because across different people with different angle kappas different visible vergence angles occur, when fixating on objects in the same distance.

Second, the majority—almost everyone according to Basmak et al. (2007)—has a positive angle kappa value. With a positive angle kappa value, the fovea is temporally displaced or there is an aberration in the pupillary axis. The case of a temporally displaced fovea is easiest to grasp. Because of angle kappa, the eyes have a natural vergence. In the case of an angle kappa of, e.g., 2° (not uncommon according to Barry et al., 1992), both eyes together have a natural vergence angle of 4° (slightly converged). As a consequence, when the eyes are perfectly parallel according to their pupillary axis, the visual axes of both eyes in sum (defined by the foveae) are converged by 4°, and if the pupillary axes of both eyes in sum are diverged by – 4°, the optical axes are perfectly parallel. In consequence, the physiological vergence is stronger than the visible vergence (see Figure 6). This would explain the overestimation effect reported by Nyguen and colleagues (2018), and also explains our results of perceived central depth in Experiment 1. Recall that in Experiment 1, the adjusted vergence for being perfectly looked at was almost 0°, that is, parallel pupillary axes, which is clearly not the correct angle for a 90 cm fixation point.

In the learning process of inferring fixation distance by observing the vergence angle, many eyes that observers see are less converged than ideal eyes with an angle kappa of zero. Imagine two persons fixating on an object in one meter distance, one person with a small and another with a large angle kappa. Because angle kappa implies natural vergence, the person with the smaller angle needs to converge more than the person with the larger angle. With having in mind that the majority has positive angle-kappa values, observers are often confronted with under-converged visible vergence angles. Observers neither know the actual vergence angle nor the angle kappa of the looker. Thus, they associate under-converged eyes with viewing distance during learning. This perfectly fits to the overestimation effect of Nyguen and colleagues, which says: Parallel eyes are perceived as being somewhat converged. Transferring it to distances means: Parallel eyes are not perceived to be referred to distances above 2 meters, but to a distance of 1 meter.

The first and the second experiment found evidence for a relatively large proximal border of direct gaze, and no distal border (or a border at infinity). It remains to be discussed whether there could be a tendency to perceive gaze more likely as direct when other reasonable fixation objects are absent. In conjugate as well as in vergence eye movements there is the possibility

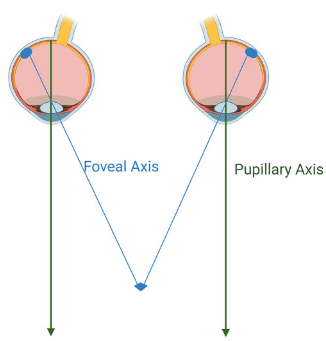

Figure 6. Exaggerated example of positive angle kappa value and the pupillary as well as foveal axis due to temporal displacement of the fovea. Created with BioRender.com.

that the presence of another object that could possibly be fixated on by the looker, could lead to a shrinking of the border limits. Another question, which remains open, is about different looker-observer distances. One may speculate whether a closer looker-observer distance leads to a measurable (i.e., not infinite) distal-cone border. Imagine a really close interaction between two people standing just a few centimeters apart from each other. It is a plausible assumption that an observer sees the difference between fixation in 20 cm distance, which induced a quite large vergence angle of 9° and a fixation distance of 120 cm, which is reflected in a vergence angle of 1.55°, if someone is standing 1 meter behind the original conversation partner. The other way around, a larger distance between looker and observer could induce an even wider proximal cone border while we would think, that distal cone border will be similar to the present experiments.

Practical implications can be found in the medical field. The distal border highlights the importance of investigating diverging eyes. Our results indicate that the observer accepts a relatively wide range of vergence angles as directed at him. In some illnesses like strabismus, diverged eyes do naturally occur (Mohney, 2007). Manifest strabismus affects 5–9% of children,[1] while latent strabismus occurs in 70–80% of the population (Graham, 1974; Kommerell & Kromeier, 2002; viz: latent strabismus is a form of strabismus that can be seen only when the eyes do not fixate a stimulus, as in, e.g., complete darkness). Patients who suffer from strabismus often report struggles in holding eye contact. Even after surgical correction patients with longstanding strabismus differ from healthy controls when it comes to eye contact (Babar et al., 2010). Our results, however, indicate that the range of vergences that are acceptable during mutual gaze is relatively large.

To conclude, we find that the cone of gaze is not only an area in the frontal plane relative to the looker and the observer, but also in the sagittal plane. The cone starts at a point between the looker and the observer and extends to infinity. Its three-dimensional shape is thus similar to the visible shape of a comet (with a ball-shaped front and a fading tail). The practical implications of this result for research on direct gaze are that exact vergence is not the most important variable, as observers accept a wide range of vergence angles for a direct gaze. In the present experiment with a viewing distance of 90 cm, we find a considerable wide range of vergence angles of about 7° per eye as supporting the perception of direct gaze.

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Authors Contribution

Linda Linke planned, conducted, analyzed and interpreted the experiments and wrote the paper. Gernot Horstmann planned and interpreted the experiments and wrote the paper.

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ORCID iDs

Linda Linke https://orcid.org/0000-0002-8579-6823
Gernot Horstmann https://orcid.org/0000-0002-2644-414X

Note

1. Because strabismus can be successfully cured, study data only include six year old children (Graham, 1974).

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