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Are You Looking at Me? Measuring the Cone of Gaze

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The processing of gaze cues plays an important role in social interactions, and mutual gaze in particular is relevant for natural as well as video-mediated communications. Mutual gaze occurs when an observer looks at or in the direction of the eyes of another person. The authors chose the metaphor of a cone of gaze to characterize this range of gaze directions that constitutes "looking at" another person. In 4 experiments using either a real person or a virtual head, the authors investigated the influences of observer distance, head orientation, visibility of the eyes, and the presence of a 2nd head on the perceived direction and width of the gaze cone. The direction of the gaze cone was largely affected by all experimental manipulations, whereas its angular width remained comparatively stable.

Keywords: gaze perception, eye contact, head orientation

Knowing whether one is the recipient of a gaze—be it the gaze of a friend or of an enemy—can be decisive in many social interactions. Given the social relevance of determining gaze direction, the psychophysics of gaze is underdeveloped. Although many articles have touched on the issue, systematic attempts to characterize humans' ability to discern gaze direction are few and far between. We first summarize the relevant studies that touch on the issue and then report four experiments that lay the foundations for a measurement of perceived gaze direction. In these experiments, we begin to explore a number of extraneous factors, such as the presence of another gazing person, that might modulate perceived gaze direction.

A number of facial and ocular cues are involved in generating the percept of gaze direction. For instance, Wollaston (1824, cited in Wade, 1998) created drawings that illustrate the influence of head orientation and facial features on perceived gaze direction. Also, the luminance configuration that results from the high contrast between the iris and the sclera is indicative for gaze direction (Ando, 2002; Langton, Watt, & Bruce, 2000; Schwaninger, Lobmaier, & Fischer, 2005).

The Social Role of Gaze

In social interactions, gaze cues provide information, regulate interaction, express intimacy, exercise social control, and facilitate goal setting (Baron-Cohen, 1995; Kleinke, 1986; Patterson, 1982). Even newborns prefer to look at faces that engage them in mutual gaze (Farroni, Csibra, Simion, & Johnson, 2002), and by the age of 4 months infants can discriminate between direct and averted gaze, even when the head is rotated independently of the eyes (Farroni, Johnson, & Csibra, 2004). With a paradigm devised by Posner (1980), gaze cues have been shown to trigger reflexive shifts of spatial attention; that is, a face looking at the side of the screen where a target is to appear facilitates responses to this cued target as compared with targets appearing in uncued positions (Friesen & Kingstone, 1998; Langton & Bruce, 1999; Ricciardelli, Bricolo, Aglioti, & Chelazzi, 2002). This effect seems to be mainly automatic and is hard to control voluntarily. Stable differences in reaction times were observed even when participants were informed that the target was more likely to appear on the uncued side (Driver et al., 1999; Friesen, Ristic, & Kingstone, 2004).

Mutual Gaze

Several studies have examined the accuracy of eye-gaze judgments. Generally, when judging a real looker or a videotaped gaze, humans are very accurate in determining the gaze direction (Anstis, Mayhew, & Morley, 1969; Gale & Monk, 2000; Symons, Lee, Cedrone, & Nishimura, 2004). Estimation errors were particularly small when the stimulus was oriented directly at the observer's face, suggesting that mutual gaze might be a qualitatively special signal (Cline, 1967). This notion, however, was criticized by authors such as Vine (1971; see also Ellgring, 1970; Lord & Haith, 1974), who referred to several studies showing fairly poor discrimination of target points in and around the face. These authors also noted that the deviation between judged gaze direction and actual looker–observer axis decreased with distance. Taken together, the evidence suggests that when in doubt or when visual information was reduced, observers tended to assume a mutual gaze.

A study by Gibson and Pick (1963) directly addressed the question of whether an observer is able to discriminate mutual and averted gazes. The experimenters instructed a looker to gaze at one of seven equidistant locations on a wall behind the observer or at the bridge of the observer's nose. At a viewing distance of 2 m, the observer judged whether he was being looked at. Additionally, the looker's head rotation was varied (–30°, 0°, or 30°). Overall, the precision of judgments was very high. Observers were able to identify displacements of the looker's iris as small as 1 min of arc. However, the range within which the observer felt the gaze directed toward him or her appeared to be of considerable width. It

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could not be determined precisely, because the effective resolution was rather limited. The center of this range varied slightly as a function of the experimenter's head rotation. That is, a head rotation of the gazing person to the left or to the right resulted in a displacement of the sector within which the observer felt looked at, in the same direction as the rotation. Martin and Jones (1982) used signal detection theory to independently examine the influence of various factors on eye-gaze discriminability and potential biases in the subject's criterion. They found a decline in discriminability with increasing looker–observer distance and decreasing lighting intensity. Additionally, at greater distances the observers were more prone to think that the looker was looking at their eyes when in fact she was not, a result that fits reports by Vine (1971). Among behaviors co-occurring with eye gaze, only smiling led to a response bias; that is participants reported more mutual eye gaze from smiling lookers whereas the eye gaze discriminability was largely unaffected (Martin & Rovira, 1982).

A recent study has shown a specific influence of mutual gaze on memory-related processes. Mutual gaze in contrast to averted gaze facilitated the processing of categorical information related to the gazing person and sped up the access of stereotypic information from semantic memory (Macrae, Hood, Milne, Rowe, & Mason, 2002). Research on gaze perception has gained importance in the context of video-mediated communications and interactions in virtual reality (Grayson & Monk, 2003). Realistic eye-gaze behavior, and specifically an avatar's mutual gaze while the participants spoke, increased the perceived quality of interactions (Garau et al., 2003; Vinayagamoorthy, Garau, Steed, & Slater, 2004).

The Cone of Gaze

On the basis of the above studies and their often varied assessments of gaze, we hypothesize that there is a range of considerable width wherein a person feels looked at. In other words, we suggest that the appropriate metaphor when thinking of gaze direction is not that of a ray, as assumed in earlier studies (e.g., Gale & Monk, 2000; Symons et al., 2004), but rather that of a cone. The cone metaphor has two decisive advantages over the ray metaphor. First, the cone metaphor can accommodate the fact that at near distances we would strictly have to distinguish between two rays of gaze, one from the looker's left eye and one from the right eye. Thus, if we adhere to the ray metaphor, we would have to generate separate hypotheses for the two eyes, at least at close viewing distances. Then, those would have to be somehow integrated into the resulting unitary percept of being looked at. The cone metaphor, on the other hand, does not require such sophistication.

Second, the cone metaphor is better suited to make predictions about the circumstances under which one should and should not feel the interception of a gaze. A small example might serve as an illustration. When you are fixating someone's left eye at close distance, this person certainly feels looked at. But when you now change your fixation to her right eye, she presumably still feels looked at, although noticing the movement of your eyes at the same time. Thus, the ray hypothesis would have to specify how the two rays may interact and whether the interception of just one ray is sufficient or necessary. The cone metaphor, on the other hand, defines a sector in space whose origin is the interpupillary point. Most important, the absolute width of the sector of space that is covered by the gaze widens with distance only according to the cone metaphor. Thus, we hypothesize that we can evade the professor's unchangeable gaze by shifting one seat to the right in the front row of a classroom. However, in the last row, such a shift of seats will not be sufficient to escape from the gaze. In the following, we take the liberty to call the range within which a person feels looked at the *gaze cone*, in anticipation of our results.

The experiments reported here were designed to examine two characteristics of this gaze cone, namely, its width and its central direction, as a function of several variables. In contrast to the vast majority of studies cited above, we opted for an interactive quantitative measure of the point where a given gaze is perceived to fall just inside the range that would be classified as looking at the observer. In the first two experiments, displays of a virtual head were used to examine the effects of looker–observer distance, head rotation, and visibility of the eyes on the width and the direction of the gaze cone. Experiment 3 explored stereoscopic displays of a virtual head, and Experiment 4 provides a reality check: Observers had to evaluate the gaze cone of a real head.

Experiment 1: The Gaze Cone of a Virtual Head

Most existing studies on gaze perception have used pictures of heads rather than real-life lookers, for obvious reasons of usability and experimental control. We followed suit and designed a virtual head based on the 3-D layout of a human head. Although the underlying model of the head was 3-D, it was at all times rendered and depicted on a 2-D monitor and thus had image quality. The objective of the experiment was to assess the tolerance range within which observers would be willing to say that the head was looking at them, as a function of three factors. In addition to the looker–observer distance and the orientation of the virtual head, whose impact on gaze direction judgments have been examined before (see Vine, 1971, for a review), we chose to vary the visibility of the looker's eyes. This latter manipulation was implemented for two reasons. First, earlier studies have shown that the accuracy of gaze direction judgments declines when visual cues are limited (e.g., Martin & Jones, 1982; Symons et al., 2004). Thus, mere occlusion of one of the looker's eyes might have a comparable effect on the observer's willingness to assume mutual gaze. Second, this manipulation allowed us to examine whether observers are able to integrate the gaze direction of both eyes of the looker into an optimized estimate of the gaze cone's direction. In particular, such integration should improve gaze direction judgments under suboptimal conditions as established by a large looker–observer distance and a rotation of the looker's head.

Method

Participants. Ten observers (4 women, 6 men), aged between 21 and 34 years ($M = 26.6$, $SD = 5.5$), participated voluntarily in the experiment. All had normal or corrected-to-normal vision.

Apparatus. A natural looking human head (see Figure 1) was rendered using the 3-D software Vizard 2.14 (2004) and displayed on a 17-in. flat screen with a resolution of $1,280 \times 1,024$ pixels and a color depth of 32 bits. The width of the virtual head was 16.5 cm and the height 25.8 cm. Its interpupillary distance was 6.4 cm. The screen size of the virtual head approximately equaled that of an adult human head at screen distance. The eyes were rendered independently and could be rotated interactively to fixate any

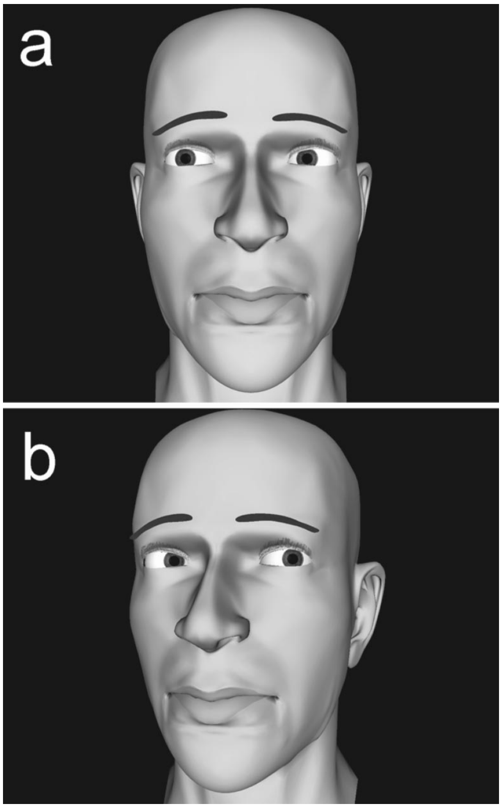

Figure 1. Pictures of the virtual head used in Experiments 1, 2, and 3: (a) Head rotation is 0°, and the eyes fixate a point to the left of the observer; (b) head rotation is 10° to the left, and the eyes fixate a point to the right of the observer.

given point in a horizontal plane defined by the observer's eye height. For the purposes of the experiment, the virtual head's lines of sight always converged at the observer's eye plane. That is, when looking straight ahead, the looker's eyes converged at the observer's interpupillary point.

The observer was seated at varying distances from the head. A height-adjustable chair combined with a chin rest ensured that the observer's eye height was 120 cm at all times. The eye height of the virtual head had been adjusted to the same height by mounting the flat screen on a table.

Design and procedure. Three factors were varied in a repeated measures design. Distance (two levels): The distance between the observer and the monitor with the virtual head was either 1 m or 5 m. The vertical visual angle subtended by the virtual head was 14.7° at 1 m and 3.0° at 5 m; the horizontal visual angles were 9.4° and 1.9°, respectively. Head orientation (two levels): The virtual head either pointed directly at the observer or was rotated around a vertical axis placed through a point between the eyes. In these cases, head rotation was 10° to its right (yaw clockwise), resulting in the nose pointing to the observer's left. Note that the eyes were not always aligned with the head, such that head orientation was independent of gaze direction. Eyes (two levels): Either both eyes of the virtual head were visible, or the right eye (from the perspective of the observer, i.e., in his right visual hemifield) was covered with a white patch. For economic reasons, distance and head orientation were blocked and counterbalanced. It was time consuming to change observer position, and blocking head orientation made the task easier. The eyes factor was varied randomly within each block.

After entering the laboratory, observers were informed about the general purpose of the study. They sat in a chair adjusted to produce the desired eye height of 120 cm. They were instructed to put their chin on the chin rest and to avoid head movements during the experiment.

In each estimation trial, observers were instructed to accomplish one of two adjustment tasks, either a centering or a decentering of the eyes of the virtual head (see Figure 2). Centering was called for if the virtual eyes initially gazed at a point around 10° to the left or to the right of the observer. This value was randomly varied by ±1° to avoid a constant starting position and at the same time to leave sufficient room for adjustment. We instructed the observer to adjust the eyes of the virtual head such that it gazed directly at him or her (centering task). Decentering was called for whenever the virtual head initially gazed directly at the observer, who was instructed to rotate the head's eyes either to the left or to the right until the virtual head subjectively stopped gazing at the observer (decentering task). The type of task was indicated by a letter in the upper left corner of the screen, and the adjustment was accomplished in steps of 0.1° using the cursor of a wireless keyboard.

The order of the trials was randomly determined for each observer. Observers pressed a button when they were satisfied with their setting. No time limit was specified. Each adjustment was accomplished three times, resulting in a total of 96 trials for each participant. The whole experiment lasted about 30 min.

Results and Discussion

Two indices were computed for each condition. The direction of the gaze cone was computed as the average of all adjustments in the centering task expressed in degrees from the observer's straight ahead. The width of the gaze cone was measured by the decentering task. It amounted to the angular difference between the leftward and rightward boundary of the sector within which gaze directions were considered as looking at the observer.

Direction of the gaze cone. We conducted a 2 × 2 × 2 analysis of variance (ANOVA) on the gaze cone's direction, using distance (1 m or 5 m), head orientation (−10° or 0°), and visible eyes (one or two) as variables. For each statistically significant effect in the ANOVAs, we report Cohen's f (Cohen, 1988) as an effect size estimate. We found significant interactions between distance and head orientation, $F(1, 9) = 14.17$, $p < .01$, $f = 0.17$, and between head orientation and eyes, $F(1, 9) = 13.20$, $p < .01$, $f = 0.17$, and a significant main effect of head orientation, $F(1, 9) = 32.51$, $p < .001$, $f = 0.66$. The rotation of the virtual head exerted a positive effect on the perceived direction of gaze; that is, it shifted to the left when the virtual head was rotated to the left. This effect was more pronounced at a distance of 1 m and when only one eye of the virtual head was visible (see Figure 3a and 3b). Additionally, the interaction of distance and eyes was significant, $F(1, 9) = 11.15$, $p < .01$, $f = 0.16$, as was the main effect of eyes, $F(1, 9) = 14.13$, $p < .01$, $f = 0.29$. When both eyes were visible, the center of the perceived gaze cone was positioned closer to the participant, particularly at a distance of 5 m (see Figure 3c). The

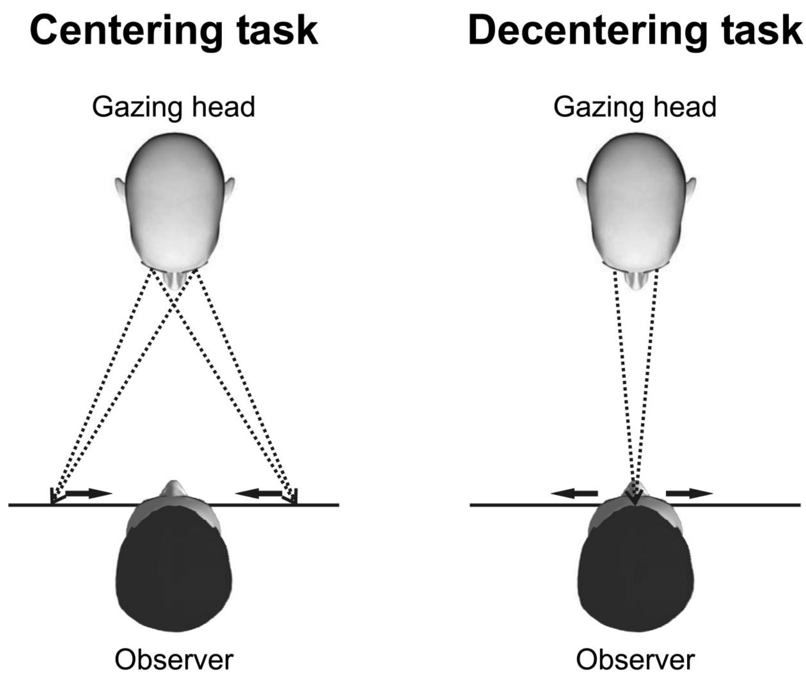

Figure 2. Illustration of the different tasks accomplished by the observers. In centering trials, participants were instructed to rotate the eyes of the gazing person from their left or right side until they felt looked at. In decentering tasks, the eyes had to be rotated to the left or right until the gazing head subjectively stopped looking at the observer.

main effect of distance and the interaction between distance, head orientation, and eyes were nonsignificant.

Width of the gaze cone. We conducted a 2 × 2 × 2 ANOVA on the gaze cone's width, using the same factors as before. No significant main or interaction effects were found. However, the average width ($M = 8.76°$, $SD = 3.21°$) differed significantly from 0, $t(9) = 8.64$, $p < .001$; that is, there was a considerable range of gaze directions that were taken to be directed (straight) at the observer. On average the cone's width amounted to 9.3° for near distances and 8.2° for far distances. The center of the cone appeared to shift toward the looker's nose whenever the virtual head was rotated.

The direction of the gaze cone was strongly affected by the distance of the virtual head from the observer and by its orientation (rotation). In particular, the perceived gaze shifted toward the direction in which the head pointed, especially when the viewing

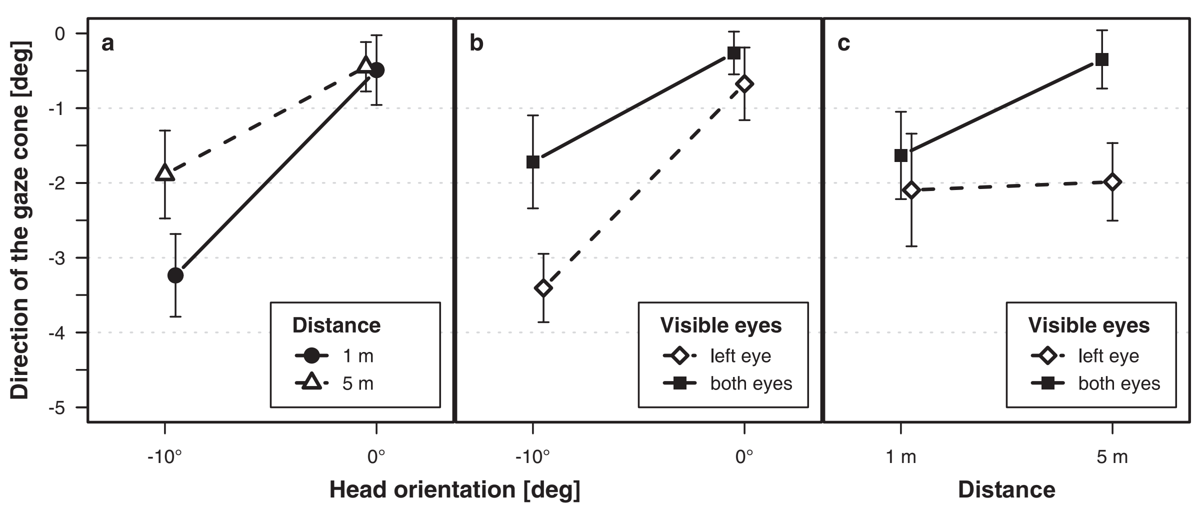

Figure 3. Experiment 1: Average positions of judged gaze direction as a function of (a) head rotation and viewing distance, (b) head rotation and visibility of one versus both eyes, and (c) viewing distance and visibility of the eyes. Error bars indicate standard errors of the mean.

distance was small and the cues were limited (only one visible eye). A comparable attractor effect was obtained by Gibson and Pick (1963) and by Martin and Jones (1982). On the other hand, the width of the gaze cone was very robust across conditions and largely unaffected by the experimental manipulations.

Experiment 2: Is the Gaze Cone Symmetric?

As Experiment 1 found significant effects of head orientation and eye visibility on gaze direction judgments, the question arises whether these effects are symmetric. For economic reasons, the virtual head had always been rotated clockwise around its yaw axis, resulting in its nose always pointing to the observer's left. Additionally, only the eye in the right visual hemifield of the observer was hidden by a white patch, in one half of the trials. Because these manipulations were not counterbalanced and differences between the processing of facial stimuli in both visual hemifields have been found in neuroimaging as well as behavioral studies, the results of Experiment 1 might reflect hemispheric asymmetries of gaze processing rather than effects of head rotation and visibility of the eyes.

Recent studies have shown that direct gazes, as compared with averted gazes, led to larger neural activity in lateralized regions of the right hemisphere (Kawashima et al., 1999; Kingstone, Tipper, Ristic, & Ngan, 2004; Pelphrey, Viola, & McCarthy, 2004). Furthermore, George, Driver, and Dolan (2001) found an increased coupling between the right fusiform cortex, a brain area known to be involved in face processing, and the amygdalae of both hemispheres for direct as compared with averted gazes. Thus, both visual hemifields seem to be processed differentially with respect to facial cues. Ricciardelli, Ro, and Driver (2002) indeed found a higher accuracy of gaze direction judgments when presenting the eye region unilaterally in the left visual hemifield as compared with the right. Additionally, the gaze direction of bilaterally presented incongruent gaze stimuli was strongly influenced by the direction of the eye in the left hemifield. To rule out such hemifield asymmetries as a potential explanation for the results of Experiment 1, we manipulated head rotation and visibility of the eyes of the virtual head symmetrically in Experiment 2.

Method

Participants. The sample consisted of 12 observers (9 women, 3 men) who had not participated in the first experiment. All had normal or corrected-to-normal vision. Their age ranged from 20 to 32 years, with an average of 23.0 years ($SD = 3.1$ years).

Apparatus, design, and procedure. The experimental configuration and the design were identical to those of the first experiment with two exceptions. Instead of rotating the virtual head only in one direction, head orientation was now varied on three levels: The virtual head was either squarely facing the observer or rotated by 10° (yaw) to the observer's left (clockwise) or right (counterclockwise). Additionally, we added a third condition to the factor visible eyes in which the left eye of the virtual head (from the perspective of the observer) instead of the right eye was covered with a white patch. The resulting design was a fully crossed $2 \times 3 \times 3$ repeated measures design with the factors distance (1 m or 5 m), head orientation (–10°, 0°, or 10°), and visible eyes (left eye, both eyes, or right eye visible). Distance and head orientation were blocked and counterbalanced; the factor visible eyes was varied randomly within each block. Observers had to accomplish all four tasks that were previously used in Experiment 1 (centering from left and right starting orientation of the eyes and decentering toward the left or right edge of the perceived cone of gaze). To shorten the experiment, we decided to repeat each trial only once, resulting in a total of 144 trials. As the observers' estimates were rather stable across repetitions in Experiment 1, this procedure seemed justified. The whole experiment, including several training trials at the beginning, lasted about 40 min. As in Experiment 1, we used two dependent measures: the direction and the width of the gaze cone.

Results and Discussion

Direction of the gaze cone. A $2 \times 3 \times 3$ ANOVA was conducted on the judged direction of gaze, using distance (1 m or 5 m), head orientation (–10°, 0°, or 10°), and visible eyes (left eye, both eyes, or right eye) as factors. The main effect of head orientation, $F(2, 22) = 36.63$, $p < .001$, $f = 0.78$, as well as the interactions between distance and head orientation, $F(2, 22) = 9.08$, $p < .01$, $f = 0.19$, and between head orientation and visible eyes, $F(4, 44) = 11.57$, $p < .001$, $f = 0.26$, were statistically significant. Comparable to the first experiment, head orientation influenced judged gaze direction. This effect was more pronounced at the short viewing distance and when only one eye of the virtual head was visible to the observer (see Figure 4a and 4b). Covering one eye affected the estimated viewing direction of the other visible eye. Its perceived viewing direction was shifted toward the side of the covered eye. This bias was most pronounced when the virtual head was oriented parallel to the observer's line of sight. Additionally, we obtained a significant interaction of distance and visible eyes, $F(2, 22) = 10.78$, $p < .001$, $f = 0.20$. The direction of the gaze cone was affected by the visibility of the eyes only at a distance of 1 m (see Figure 4c). All other main and interactive effects were nonsignificant.

Width of the gaze cone. A $2 \times 3 \times 3$ ANOVA was conducted on the gaze cone's width using the same factors as before. No significant main or interaction effects were found. The average width ($M = 8.17°$, $SD = 2.17°$) differed significantly from 0, $t(11) = 13.04$, $p < .001$.

The results of this second experiment were fully comparable to those of Experiment 1. The influence of the gazer's head orientation on judged gaze direction as well as the modulating effects of viewing distance and visibility of the eyes were replicated. Covering one of the virtual head's eyes produced a roughly symmetric effect on the judged direction of the gaze cone. Thus, differences in subjective gaze directions when seeing one versus both eyes cannot be explained by a differential processing of the two visual hemifields. Again, the gaze cone was shown to be rather wide and proved to be stable across the experimental manipulations.

Experiment 3: The Gaze Cone Using a Stereoscopic Presentation

In Experiments 1 and 2, the width of the gaze cone was considerably larger than could be expected on the basis of the results obtained with real heads by Gibson and Pick (1963). Maybe this discrepancy arises because cues to visual depth, which might

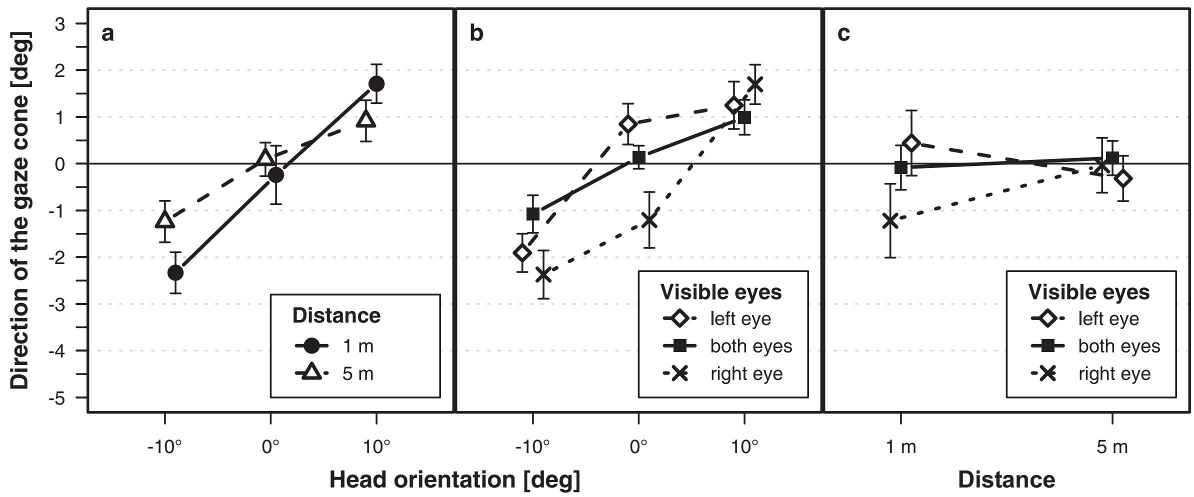

Figure 4. Experiment 2: Average positions of judged gaze direction as a function of (a) head rotation and viewing distance; (b) head rotation and visibility of the left, the right, or both eyes of the virtual head; and (c) viewing distance and visibility of the eyes. Error bars indicate standard errors of the mean.

enhance the observer's ability to differentiate mutual from averted gazes, were rather limited in the current experiment. A recent study by Imai and colleagues demonstrated that the accuracy of gaze direction judgments increases when using stereoscopic displays (Imai, Sekiguchi, Inami, Kawakami, & Tachi, 2006). However, the authors examined gaze direction accuracy only when looking at a working area below the observer's eye height. To test whether the mutual gaze cone's width is also affected by added visual depth cues, we displayed the virtual head stereoscopically in the current experiment.

Also, our first two experiments have demonstrated that the gaze cone's direction was susceptible to variations of the looker's head orientation and the visibility of his eyes. Thus, specific characteristics of the virtual head, whose gaze had to be judged, influenced perceived gaze direction. Given this susceptibility of judgments to extraneous aspects of the gazing head, it appeared worthwhile to explore whether this effect extends to stimuli outside of the gazer. We started by asking whether a social stimulus entirely irrelevant to the task also exerts an influence on the observer's gaze direction estimates. Thus, we added a second head to the visual scene in one half of all trials. This head always gazed directly at the observer, and we examined its effect on the perceived gaze direction of the primary head.

Method

Participants. The sample consisted of 10 volunteers (6 women, 4 men) with normal or corrected-to-normal vision who had not participated in the first two experiments. Their average age was 26.1 years (SD = 3.3 years), with a range of 22 to 33 years.

Apparatus. The same virtual head with interactively movable eyes was used as in Experiments 1 and 2 (see Figure 1), but it was placed on a uniformly colored pillar with a height of 120 cm in a virtual laboratory room and displayed on a large rear-projection screen (260 × 192.5 cm) with a color depth of 32 bits. This viewing setup was chosen to accommodate the second head. The projection allowed for stereoscopic viewing by use of two projectors with a resolution of 1,400 × 1,050 pixels each. The light of the two projectors was linearly polarized in orthogonal planes. Participants wore matching polarization filters such that each eye received a unique image. The positioning of the observer in front of the projection screen was the same as in Experiments 1 and 2.

Design and procedure. Four factors were varied in a repeated measures design. Distance (two levels): The simulated distance between the observer and the virtual head was either 1 m or 5 m. The virtual head had the same size as in the first two experiments, and its visual angles were comparable. Head orientation (3 levels): The virtual head was either aligned with the observer's line of sight or rotated by 10° (yaw) to the left or to the right. Eyes (two levels): Either both eyes of the virtual head were visible, or the right eye (from the perspective of the observer) was covered with a white patch. Distractor head (two levels): In one half of the trials, another virtual head, similar to that displayed in Figure 1, was shown on a pillar to the right of the target head, as seen by the observer. This additional head was always oriented directly at and always gazed straight at the observer. Distance and head orientation were blocked and counterbalanced; the other factors were varied randomly within each block. All factors were fully crossed and presented in conjunction with all four tasks (centering from left and right starting orientation of the eyes and decentering toward the left or right edge of the perceived cone of gaze). Each trial was repeated once, yielding a total of 192 trials. The whole experiment lasted about 50 min. As in the other experiments, we used two dependent measures: the direction and the width of the gaze cone.

Results and Discussion

Direction of the gaze cone. In a first step, a 2 × 3 × 2 × 2 ANOVA was conducted on the judged angular direction of gaze, using distance (1 m or 5 m), head orientation (–10°, 0°, or 10°), visible eyes (one or two), and the presence of the distractor head as factors. We found a significant main effect of distance, $F(1, 9) = 5.99$, $p < .05$, $f = 0.19$. A small bias to shift the center of the sector to the right was observed at a distance of 1 m (M = 0.70°, SD = 1.83°) but not at 5 m (M = 0.09°, SD = 1.34°). The interactions between distance and head orientation, $F(2, 18) = 26.22$, $p < .001$, $f = 0.32$, and between head orientation and visible eyes, $F(2, 18) = 7.68$, $p < .01$, $f = 0.20$, were significant, too. The orientation of the gazer's head tended to attract the position of the gaze cone only at a distance of 1 m and when merely one gazing eye was visible (see Figure 5a and 5b). Additionally, we found a significant interaction of distance and visible eyes, $F(1, 9) = 5.98$, $p < .05$, $f = 0.12$, and a significant main effect of visible eyes, $F(1, 9) = 12.56$, $p < .01$, $f = 0.27$. When only one eye was visible, observers tended to adjust the head's gaze too far to their right (M = 0.83°, SD = 1.80°). This bias was absent when both eyes were visible (M = −0.03°, SD = 1.32°). Differences in the direction of the gaze cone as a function of eye visibility were more pronounced at a viewing distance of 1 m (see Figure 5c). The main effect of the presence of the distractor head was also significant, $F(1, 9) = 5.35$, $p < .05$, $f = 0.09$. When the distractor head was present in the scene, observers positioned the gaze of the relevant head closer toward themselves (M = 0.26°, SD = 1.65°) compared with scenes without the additional head (M = 0.54°, SD = 1.61°). All other main and interactive effects were nonsignificant.

Width of the gaze cone. In a second step, we conducted a 2 × 3 × 2 × 2 ANOVA on the gaze cone's width using the same factors as before. No significant main or interaction effects could be found. The average width (M = 6.74°, SD = 5.17°) differed significantly from 0, $t(9) = 4.13$, $p < .01$.

The results using a stereo display were largely comparable to those obtained in Experiments 1 and 2, where 2-D stimuli had been displayed on a flat screen. Again, the position of the gaze cone was attracted by the orientation of its virtual head (see also Gibson & Pick, 1963), in particular at small viewing distances and when only one gazing eye was visible. Of interest, the distractor head, gazing directly at the observer, led to robust adjustments of the direction of gaze toward the observer. This was the case across all other variations. Thus, the second virtual head, despite the task to ignore it, influenced the target's gaze direction but had no impact on the gaze cone's width. The discriminability, as indicated by the gaze cone's width, remained stable across all experimental manipulations.

To compare the gaze cone's width between flat-screen viewing (Experiments 1 and 2) and the stereoscopic display (Experiment 3), we conducted an ANOVA using experiment as a between-subjects factor and the gaze cone's width as a dependent measure. We did not obtain a significant effect, $F(2, 31) < 1$. That is, despite the trend of the gaze cone to be somewhat smaller with stereoscopic presentation, the width of the gaze cone remained stable across the first three experiments. The additional visual depth cue provided in Experiment 3 had no substantial effect on the observer's willingness to report mutual gaze for a considerable range of gaze directions. This result is in contrast to a recent study that focused on observers' gaze direction accuracy when looking at a working area at desk height (Imai et al., 2006). Thus, gazes in and around the eye region that are capable of inducing a feeling of being looked at might qualitatively differ from gaze direction judgments in other parts of the visual field, as they are not affected by added visual depth cues.

Experiment 4: The Gaze Cone of a Real Head

One might argue that the results obtained in Experiments 1, 2, and 3 cannot be generalized to everyday gaze perception because pictures, including virtual environments, remain rather limited in resolution and are highly artificial. Such worries are to be taken seriously, as the discriminability of another's line of gaze has been found to be noticeably larger when a real person is used as the looker (Cline, 1967; Gibson & Pick, 1963). Therefore, we replicated our assessment of the gaze cone by introducing a real-life situation that was otherwise comparable to the setup used in Experiments 1 to 3.

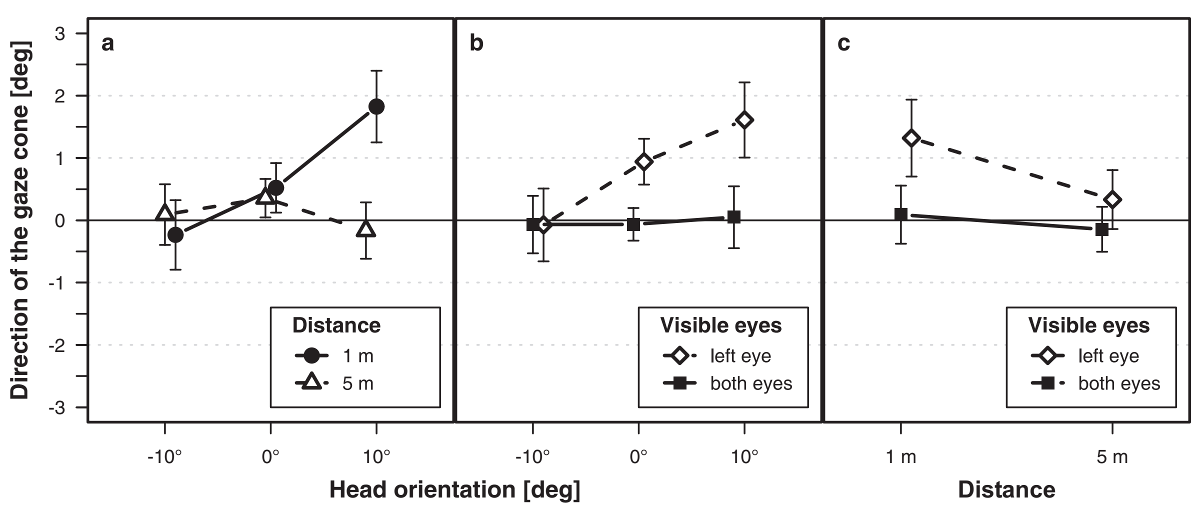

Figure 5. Experiment 3: Average positions of judged gaze direction as a function of (a) head rotation and viewing distance, (b) head rotation and visibility of one versus both eyes, and (c) viewing distance and visibility of the eyes. Error bars indicate standard errors of the mean.

Figure 6. Picture of the experimenter's assistant, whose gaze could be remote controlled by the observer in Experiment 4.

Method

Participants. Ten participants (3 women, 7 men) with normal or corrected-to-normal vision voluntarily participated in the experiment. Their mean age was 24.2 years (SD = 1.7 years), with a range of 22 to 27 years. None of them had participated in Experiments 1 to 3.

Apparatus. The setup was constructed to be comparable to the other experiments, but a real person instead of a virtual head gazed at the observer (see Figure 6). The experimenter asked an assistant to gaze at the participant, who was seated at varying distances from the assistant. The assistant's head was fixed using an adjustable chin rest to place his eyes 120 cm above the ground. The chin rest allowed for a yaw rotation of the assistant's head by 10°. The observer's head was also fixed, using a chin rest with same height. A wooden bar with a length of 4 m was mounted directly beneath the observer's eyes. At the rear side of the bar, invisible to the observer but visible to the experimenter's assistant, a motor-powered reference point could be moved smoothly along the bar. By fixating this moving reference point, the experimenter's assistant managed to produce smooth eye movements, which could be directed by the observer using a left–right switch that caused the electric motor to move to the left, move to the right, or stop (center switch position). Thus, the observer directed the assistant's direction of gaze.

Design and procedure. The design was markedly curtailed because the procedure was rather exhausting for the experimenter's assistant, who served as the looker. Two factors were varied in a repeated measures design. Distance (two levels): The distance between the observer's and the assistant's eyes was either 1 m or 5 m. The visual angles were largely similar to those in Experiments 1, 2, and 3. Head orientation (two levels): The assistant's head was either aligned with the observer's line of sight or rotated by 10° to the observer's left (yaw clockwise). Distance was blocked and counterbalanced across participants, and the assistant's head orientation was now varied randomly within each block to reduce potential adaptation effects.

Observers were instructed to accomplish the same tasks as before; that is, they directed the assistant to rotate his eyes to gaze directly at them (centering task) or at the boundaries of the cone of gaze (decentering task; see Figure 2). The trial order was determined randomly for each observer, and the experimenter moved the reference point to the corresponding initial positions while the participant kept his or her eyes closed. The participant then opened his or her eyes and directed the assistant's gaze according to the specified task. No time limit was imposed on the adjustments. Each trial was repeated once, resulting in a total of 32 trials for each participant. The whole experiment, including the demonstration of the equipment, lasted about 30 min. As in the other experiments, we separately computed the center and the width of the gaze cone as dependent measures.

Results and Discussion

Direction of the gaze cone. We conducted a 2 × 2 ANOVA on the angular direction of the gaze cone, using distance (1 m or 5 m) and head orientation (−10° or 0°) as factors. We found a significant main effect of head orientation, $F(1, 9) = 6.69$, $p < .05$, f = 0.41. Observers tended to displace the direction of the gaze cone toward the direction in which the assistant's head was rotated (head rotation 0°: M = –0.06°, SD = 0.83°; head rotation –10°: M = –0.80°, SD = 1.03°). The main effect of distance and the interaction between distance and head orientation failed to reach statistical significance. Figure 7 shows the estimated direction of

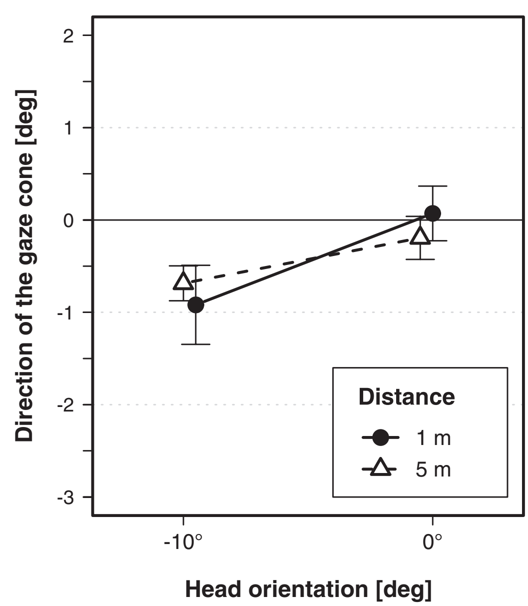

Figure 7. Experiment 4: Average positions of judged gaze direction as a function of head rotation and viewing distance. Error bars indicate standard errors of the mean.

Table 1
Means and Standard Deviations of the Gaze Cone's Width as a Function of Viewing Distance Within Each Experiment

	Distance 1 m		Distance 5 m	
Experiment	*M*	*SD*	*M*	*SD*
1	9.34° (16.36 cm)	4.39° (7.72 cm)	8.19° (71.61 cm)	2.91° (25.55 cm)
2	8.50° (14.88 cm)	3.20° (5.63 cm)	7.85° (68.63 cm)	1.93° (16.91 cm)
3	7.17° (12.58 cm)	6.25° (11.12 cm)	6.32° (55.36 cm)	5.06° (44.50 cm)
4	8.12° (14.21 cm)	3.70° (6.52 cm)	3.90° (34.09 cm)	1.24° (10.86 cm)

the gaze cone as a function of head rotation and viewing distance to allow for a comparison with Experiments 1 to 3.

Width of the gaze cone. In a second 2 × 2 ANOVA on the width of the gaze cone, using the same factors as before, the main effect of distance was statistically significant, $F(1, 9) = 21.21$, $p < .01$, $f = 0.78$. At a distance of 1 m, the gaze cone's width was considerably larger ($M = 8.12°$, $SD = 3.70°$) than at a distance of 5 m ($M = 3.90°$, $SD = 1.24°$). All other main and interaction effects were not significant.

As in Experiments 1 to 3, the head rotation of the gazing person affected the direction of the gaze cone by exerting an attraction; however, this effect was robust at both viewing distances. Moreover, the angular width of the gaze cone was smaller at large viewing distances, an effect that was not found using virtual 2-D or 3-D displays. We can only speculate as to whether resolution or attributes of the particular looker were responsible for the effect. When considering metric instead of angular values,[1] the gaze cone's width increased as a function of looker–observer distance in all four experiments (see Table 1). This effect, however, was less pronounced in Experiment 4.

General Discussion

We have explored what it means to receive another person's gaze. The subjective direction of gaze is best thought of in terms of a cone rather than a ray. The metaphor of a gaze cone has prompted us to measure both the center and the boundaries of this would-be cone. Generally speaking, the center of the cone was easily shifted by a number of extraneous factors, such as the presence of a third person. The width of the cone, on the other hand, remained rather stable.

The width of the gaze cone ranged between 4° and 9° of visual angle, depending on the stimulus and the observer's distance from the looker. Of interest, the width of the gaze cone was much larger than it needs to be with respect to the observer's visual acuity. Earlier assessments of difference thresholds of a looker's gaze directions have been reported to be around 1° of visual angle or even considerably lower (Symons et al., 2004). Why is the cone of gaze so wide compared with humans' acuity? One answer could be the notion that gaze detection is optimized for close distances. At 1 m from the observer, a looker's gaze needs to shift by 3.7° to move from being directed at the observer's left eye to the right eye (assuming an interpupillary distance of 6.5 cm). Thus, all gazes within this 3.7° range are being directed at the observer. This range reduces to 0.7° at a looker–observer distance of 5 m. The cone of gaze should thus narrow considerably if the observer closes one eye or if the observer moves farther away from the looker. In the latter case, we did find a significant narrowing of the gaze cone (Experiment 4), but closing one of the looker's eyes did not have a similar effect. Given humans' extraordinarily high visual acuity and the high social value of accurately judging gaze direction, the gaze cone has turned out to be surprisingly wide and stable with observer distance.

The gaze cone is also surprisingly vulnerable to being shifted by extraneous cues, such as the looker's head orientation. The orientation of the looker's head attracted the perceived direction of the gaze cone toward the head direction. This attraction effect was particularly strong when the looker–observer distance was small and only one of the looker's eyes was visible. Comparable results were obtained by Anstis and colleagues (1969), Cline (1967), and Gibson and Pick (1963). This effect could not simply be explained by hemispheric asymmetries of gaze processing (Ricciardelli, Ro, & Driver, 2002) because it proved to be stable for both visual hemifields (Experiment 2). It is most likely due to the shift of the pupil out of the center of the visible part of the eyeball. Anstis and coworkers observed the analogous result using an artificial eye (a table-tennis ball with a hole representing the pupil) partly covered by a diaphragm mounted on an artificial socket. Turning the diaphragm in one direction caused the gaze judgments to shift in the opposite direction, a finding that is equivalent to results obtained in the current study (see Anstis et al., 1969, p. 477, for a detailed explanation). Ando (2002; see also Ando, 2004) produced a similar effect simply by manipulating the luminance at one side of the sclera. Apparently, this luminance-induced shift of perceived gaze direction could be reduced by seeing both eyes of the looker, which indicates that the observer was able to combine the gaze direction of both eyes into an improved estimate of the looker's viewing direction.

The results of our third experiment indicate that perceived gaze direction is highly vulnerable not only to immediate configurational information but also to rather remote contextual information. The fact that additional situational cues, such as the gaze of a distractor head, were integrated in the gaze estimation is truly remarkable. The mere presence of a third party influences per-

[1] Metric values are certainly not preferable when analyzing the effects of the experimental manipulations on the width and the direction of the gaze cone, because they strongly vary with viewing distance. They are, however, useful to illustrate the scaling of the gaze cone's width with varying viewing distances.

ceived gaze direction. It would be interesting to examine whether this effect is yet enhanced when adding multiple lookers to the situation, which might be important in the context of multiparty conversations. Moreover, it remains to be seen whether and how the third party's gaze direction, which was thus far always directed at the participant, may modulate perceived gaze. When the looker was represented as a 2-D image, larger looker–observer distances caused an attraction of the judged gaze direction toward the looker–observer axis. That is, the observer increasingly estimated the direction of the gaze cone as pointing directly at him or her with larger distances. This result is consistent with previous findings (Ellgring, 1970; Lord & Haith, 1974; see Vine, 1971, for a review). However, the width of the gaze cone, as expressed in angles, was largely unaffected by an increase in the looker–observer distance. Expressed in metric values, the gaze cone's width increased with looker–observer distance. This effect was significantly reduced when using a real looker instead of a virtual head. One could attribute this tightening of the gaze cone to higher realism and resolution in the real scene. However, it cannot be entirely ruled out that the looker in Experiment 4 provided some configurational facial or other cues that facilitated the detection of his gaze at the larger viewing distance. Already Gibson and Pick (1963) were favoring the use of virtual faces or photos to rule out such interpretations.

The existence of a gaze cone of considerable width, which we demonstrated in the present experiments, should in principle facilitate video-mediated communications and interactions in immersive virtual realities. The occurrence of real-life eye contact does not seem to be a precondition for a feeling of being looked at. For the case of videoconferences, however, where the camera is typically mounted on top of the monitor and the corresponding video image is placed beyond it, one must examine whether the gaze cone has a comparable extent in the vertical direction. Some evidence that the vertical extent might even be larger than the horizontal was reported by Cline (1967), who found a larger threshold for the vertical compared with the horizontal orientation when directly estimating a looker's gaze direction. Additionally, in a study by Lord and Haith (1974), participants reported eye contact in nearly half of those cases in which the looker was actually fixating his or her mouth from close viewing distances (103 cm or 176 cm, respectively). Comparable results were reported by Chen (2002).

Recently, gaze cues in special populations have been examined, for example, in autistic children (Ristic et al., 2005) and in schizophrenic patients (Langdon, Corner, McLaren, Coltheart, & Ward, 2006). Our method for the measurement of the gaze cone characteristics might facilitate the assessment of gaze perception in special populations. For instance, patients suffering from social phobia are supposed to avoid eye contact in social situations. Using objective measures provided by an eye tracker, Horley and colleagues found that these patients, in contrast to a matched control group, avoided scanning the eye region of facial stimuli, especially when an angry facial expression was shown (Horley, Williams, Gonsalvez, & Gordon, 2003, 2004). Perhaps the reason for this behavior is a significantly widened cone of gaze. We are currently examining this hypothesis in our laboratory.

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