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Psychophysics of perceiving eye-gaze and head direction with peripheral vision: Implications for the dynamics of eye-gaze behavior

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Abstract. Two psychophysical experiments are reported, one dealing with the visual perception of the head orientation of another person (the 'looker') and the other dealing with the perception of the looker's direction of eye gaze. The participant viewed the looker with different retinal eccentricities, ranging from foveal to far-peripheral viewing. On average, judgments of head orientation were reliable even out to the extremes of peripheral vision (90° eccentricity), with better performance at the extremes when the participant was able to view the looker changing head orientation from one trial to the next. In sharp contrast, judgments of eye-gaze direction were reliable only out to 4° eccentricity, signifying that the eye-gaze social signal is available to people only when they fixate near the looker's eyes. While not unexpected, this vast difference in availability of information about head direction and eye direction, both of which can serve as indicators of the looker's focus of attention, is important for understanding the dynamics of eye-gaze behavior.

1 Introduction

Like so many facets of nonverbal communication, signaling by eye gaze is phenomenologically transparent, allowing the perceiver to effortlessly know much about the other's attentional focus, intentions, and desires (Baron-Cohen 1995; Tooby and Cosmides 1995). Contrasting with the phenomenological transparency of eye-gaze signaling is its computational complexity. Just being able to perceive the other person's attentional focus ('joint attention') is a computational feat. It requires perceiving the distance and direction to the other's head; perceiving the orientation of the other's head; perceiving the orientation of the eyes within the other's head; and, then, on the basis of these, constructing the line in space representing the other's gaze direction. Any object perceived to be on this line, which also requires distance perception, is then a candidate for the other's attentional focus.

Because of the intimate connection between visual perception and eye-gaze processing, the dynamics of eye-gaze behavior reflect the social signals that are and are not perceptible to the interactants. Thus, a full understanding of social interaction mediated by eye gaze requires psychophysical research to elucidate which signals can be sensed by the interactants. So far, there has been a modicum of research, mostly by vision scientists, devoted to the psychophysics of gaze direction, whether the eyes are directly observed or just the head (Anstis et al 1969; Cline 1967; Ehrlich and Field 1993; Gale and Monk 2000; Gibson and Pick 1963; Imai et al 2006; Langton et al 2000, 2004; Poppe et al 2007; Ricciardelli et al 2000; Sinha 2000; Symons et al 2004; Teske 1988; Watt et al 2007). Ultimately, the perceived social signals are used to attempt to gauge the mental states of the other, thus constituting the "psychophysics of the social world" (Tooby and Cosmides 1995). The dynamics of this social interaction go deeper than simple registration of social signals and linking them to first-order mental states, for each interactant is aware of being represented recursively within the experience of the other ("the spiral of reciprocal perspectives"—Laing et al 1966). The role of eye gaze in nonverbal communication has long been of interest to researchers in communication, social psychology, and developmental psychology (eg Adams and Kleck 2005; Argyle and Cook 1976; Baron-Cohen 1995; Kendon 1967; Kleinke 1986; Moore and Dunham 1995; Patterson 1983; Rutter 1984) and is now the focus of considerable research by scientists interested in communication through electronic media, such as video conferencing and virtual reality (eg Bailenson et al 2002, 2005; Garau et al 2003; Grayson and Monk 2003; Monk and Gale 2002; Poppe et al 2007; Vertegaal et al 2001).

Earlier psychophysical research on eye gaze, cited above, has been largely concerned with how well the perceiver is able to sense the direction of the looker's eye gaze when the perceiver is fixating the eyes of the looker (ie not using peripheral vision). That research has shown that perceivers are exquisitely sensitive to the eye gaze of the looker both when it is directed toward the perceiver ('mutual eye gaze') and when it is directed at other objects ('joint attention'). However, eye-gaze sensing is imperfect, for besides some degree of imprecision (variability), there are constant errors in judgment as well, especially when the looker's head is not viewed straight on by the perceiver (Anstis et al 1969; Gibson and Pick 1963; Todorović 2006). There has also been an attempt to determine what visual information about the eyes relative to the head (eg visibility of the sclera on either side of the pupil) signifies looking direction.

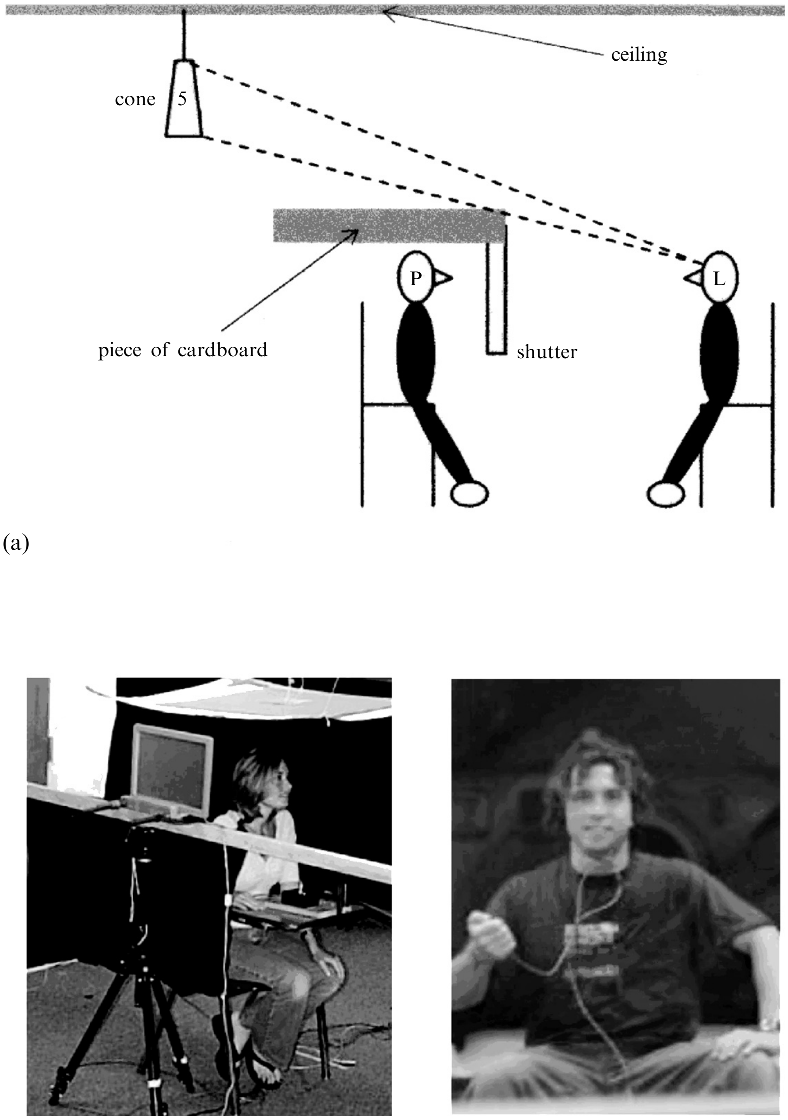
The visual stimuli signifying the looker's eye-gaze direction are of small angular extent, even when the looker is within a meter or two of the perceiver. Stimuli of small angular extent are best sensed when fixated by the perceiver, for fixation causes the retinal images to fall on the perceiver's foveal regions, where visual acuity is greatest. Thus, perceivers seeking the social signals associated with eye gaze will often fixate the looker's eyes. However, there are plenty of situations where fixating the looker's eyes is impossible or not feasible. For example, it is not possible to see the eyes of a looker who is wearing dark sunglasses or who is facing away, nor is it feasible to track the eye gaze of all interactants in a small group. However, if one wishes to know the attentional focus of another person, monitoring that person's head orientation is often a good substitute for monitoring the person's eye gaze, because people typically align their heads with objects of interest shortly after directing their gaze toward them (directing the eyes way off to one side quickly results in physical discomfort). Because the head is a much larger visual stimulus than the eyes, the social signals associated with the facing direction of the head are still quite accessible in peripheral vision despite the lower visual acuity. This means that when we wish to monitor the attentional focus of another, as in a small group setting, we can do so without having to fixate the other. Also, because maintaining mutual gaze for extended amounts of time can violate social norms in most social settings (Argyle and Dean 1965), use of peripheral vision to monitor the attentional focus of others avoids some of the awkwardness associated with staring.

The purpose of the present study is to measure psychophysically how well perceivers using peripheral vision can sense the attentional focus of another person from either the facing direction of the person's head or the person's eye gaze. In experiment 1 we are concerned with sensing head direction and used live people as the lookers. In experiment 2 we are concerned with sensing eye gaze and used photographs of lookers displayed on a CRT monitor.

2 Experiment 1

2.1 *Method*

2.1.1 *Participants.* In the main condition of the experiment, nine participants (five male and four female, aged 21 to 29 years) were recruited from the University of California Santa Barbara community and were paid for their participation. In addition, the first



(a)

(b) (c)

Figure 1. (a) Side view of the setup with depiction of the participant (P) and the looker (L). (b) Photograph of participant with cardboard above, LCD shutter to her right, and pointing apparatus on the desktop. (c) Participants' view of the looker (the third author) as seen through the open LCD shutter.

author (male, age 55 years at the time) participated without pay. All ten participants were screened with a Keystone orthoscope for stereovision and for visual acuity of at least 20/40 without eyeglasses (which no one wore in the experiment). The ten participants were tested with a male looker, L1 (figure 1c). To check on the generality of the results, four of these ten participants together with one new participant (four male and one female) were tested in a control condition (Pusch 2001) with a female looker L2, shown in the participant's position in figure 1b.

2.1.2 *Setup and apparatus.* The setup involved the looker and participant, seated on chairs in a laboratory room (figure 1). For the data to be presented here, L1, the third author, was also the experimenter; this was possible because the entire procedure

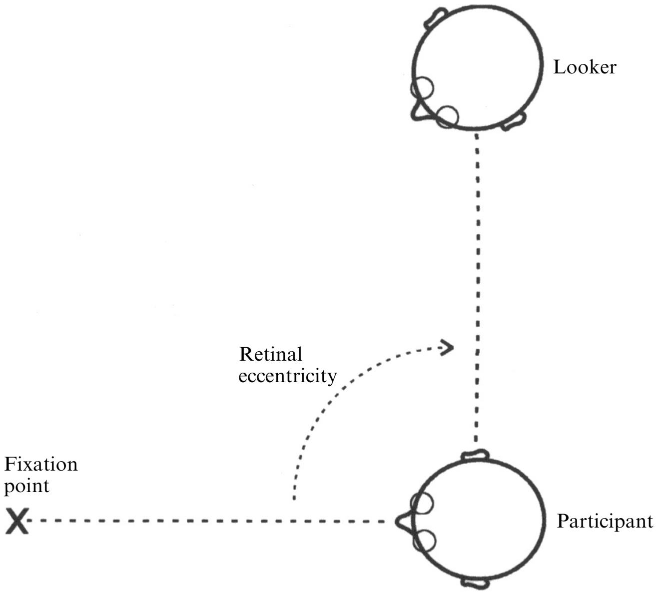


Figure 2. Schematic view of the setup. The fixation point was the lens of the video camera used to monitor that the participant maintained fixation. Varying the position of the camera relative to the looker caused the looker to assume different values of retinal eccentricity within the participant's field of view.

was computerized. (To confirm the validity of this procedure, some data were collected with L2 and with the third author as the experimenter in the control condition—Pusch 2001.) The distance between looker and participant was kept constant at 2 m; a black felt cloth was mounted behind the looker to improve the visibility of the looker (figure 1c). Both the looker and the participant assumed different head-facing directions during the experiment, and both employed binocular viewing. By placing the fixation target at different locations relative to the looker, the direction of the looker was manipulated relative to the participant's straight-ahead (figure 2); 0° signifies that the looker was directly in front of and fixated by the participant, meaning that the image of the looker fell on the high-acuity foveal region. To minimise discomfort from the eyes being turned to one side or the other, the participant's head always faced the fixation target, thus being aligned with the eyes. When the looker was in a different direction from the fixation target ('peripheral viewing'), the image of the looker appeared at some other retinal location with reduced visual acuity. The angular separation between the center of the looker's face and the participant's direction of fixation (or, within the eye, between the center of the retinal image of the looker's face and the fovea) is referred to as 'retinal eccentricity'. The binocular visual field in adult humans is roughly elliptical in shape and, at its limits, measures 200° horizontally by 130° vertically (Harrington 1971). The horizontal field of view of each eye is asymmetric because of the nose and other facial features, thus measuring 100° for the temporal region (right visual field for the right eye and left visual field for the left eye) and 60° for the nasal region. Thus, the maximum horizontal eccentricity for each eye is 100°. Figure 2 depicts a retinal eccentricity of 90°, arranged so that the looker appears in the participant's right visual field. The other two retinal eccentricities used were 0° and 45°, with the latter also in the right visual field. For 0°, the participant faced and fixated the looker. For 45° and 90°, a tripod-mounted video camcorder at the eye level of the looker was positioned in the room, and the participant binocularly fixated its lens. We did not use an eye tracker to insure proper fixation, but video recordings with the zoomed-in camcorder were made of the participant's eye gaze for azimuths other than 0°; these were subsequently reviewed by the experimenter to determine the incidence with which participants failed to maintain fixation of the camera lens. The very low incidence of failure to maintain fixation means that the performance data are valid.

On each trial, the computer issues synthesized speech to the looker through earphones, specifying the visual target to be faced and fixated. The targets were nine numbered cones hanging from the ceiling at different azimuths with respect to the participant but at a constant 30° elevation (figure 1). A cardboard sheet above the participant prevented him/her from seeing any of the cones. These cones were at the following azimuths relative to the participant: −80°, −60°, −40°, −20°, 0°, 20°, 40°, 60°, and 80°, with 0° indicating that the looker was facing the participant and negative values indicating that the looker was facing to the left of the participant, which for the 45° and 90° eccentricities also means facing behind the participant. Because of the rectangular shape of the laboratory, the cones were placed in the room at different distances from the looker and at different distances from the ceiling, but their coordinates were such that they were at the desired azimuths and always 30° above the direction to the participant. The looker wore a small laser pointer on the head that was aimed straight ahead but angled upward by 30°. When the looker turned the head to face the azimuth of the specified cone, he or she fixated the cone with the eyes and used the laser pointer to illuminate the desired cone. Because of the upward tilt of the pointer, the looker was able to keep the head level while fixating and illuminating the cone. This method allowed quick and accurate stimulus generation with a live looker. The looker and participant were visually separated by an LCD shutter which was positioned 60 cm from the participant (figure 1b); it switched from opaque to transparent under computer control. The looker was not visible to the participant when the shutter was opaque. Figure 1c shows L1 as seen through the open shutter from the participant's location. A graspable pointer was mounted on the desktop just in front of the participant (figure 1b). The participant rotated the pointer so as to be parallel to the facing direction of the looker's head. The pointer was attached to a potentiometer that provided a continuous voltage, via an Adaptec I/O card, to the 700 MHz Pentium III computer used to run the experiment. With calibration of the pointer, the voltages were read out as directions measured in degrees.

2.1.3 *Procedure.* For each block of trials, corresponding to the three retinal eccentricities of 0°, 45°, and 90°, the camcorder was positioned in the room relative to the looker to achieve the desired eccentricity. In addition, the participant's chair and the LCD shutter were properly adjusted. Once the block was underway, the participant maintained fixation of the lens of the camcorder at all times during stimulus presentation. On each trial within a block, the computer gave the trained looker a verbal command about which numbered cone to fixate; the looker then turned the head to align it with the appropriately numbered cone using the laser pointer mounted on his/her head and confirmed the correct facing direction with a button-press sensed by the computer. On trials where the participant was able to see the looker's head moving, the LCD shutter was open from the moment the looker was told the target number until 2 s after the looker confirmed facing the cone. On trials where the participant saw only the stationary facing direction of the looker, the shutter opened for 2 s after the looker confirmed being in the correct facing direction. After the shutter closed on both types of trials, the participant judged the looker's facing direction by using the preferred hand to align the haptic pointer with the looker's facing direction. The participant was allowed to look down at the pointer during this judgment phase. Each of the nine facing directions (−80° to 80°) was presented three times for each of the two stimulus conditions (moving and stationary head) for a total of 54 trials. The order of the 54 trials was randomized. Upon completion of the block of trials for a given eccentricity, the camcorder, chair, and shutter were then adjusted for the next eccentricity. The three eccentricities were presented in counterbalanced order across participants. The 162 trials took about 1 h to complete for each participant.

2.2 *Results and discussion*

Because the data obtained with L2 were very similar to those obtained with L1 for the four participants who performed the experiment with both lookers (see Pusch 2001 for more details), we report only the data for the ten participants with L1. Figure 3 gives the mean judged directions, averaged over the ten participants, for each facing direction in each of the six conditions (three eccentricities crossed with moving/stationary). Because the functional relationship between looking direction and judged looking direction is approximately linear, we quantified the performance of individuals for each condition by calculating the slope of the best-fitting linear function (ie of the form: judged looking direction = slope × looking direction + intercept).[(1)] A 2×3 repeated-measures ANOVA with terms for stimulus motion (stationary or moving) and retinal eccentricity (0°, 45°, or 90°) was conducted using the resultant slope values (shown in figure 4). Significant main effects of stimulus motion ($F_{1,9} = 5.46$, $p = 0.044$, $\eta_p^2 = 0.38$) and retinal eccentricity ($F_{2,18} = 31.97$, $p < 0.001$, $\eta_p^2 = 0.78$) were qualified by a significant interaction between stimulus motion and eccentricity ($F_{2,18} = 12.0$, $p < 0.001$, $\eta_p^2 = 0.57$). To further assess the effect of stimulus motion, slope values for moving and stationary stimuli were directly compared to one another at each retinal eccentricity. Paired-sample t-tests indicated that stimulus motion did not affect slopes at 0° ($t_9 = 1.815$, $p = 0.103$) and 45° ($t_9 = 1.023$, $p = 0.333$) retinal eccentricities, but slopes were significantly larger when viewing moving than when viewing stationary stimuli

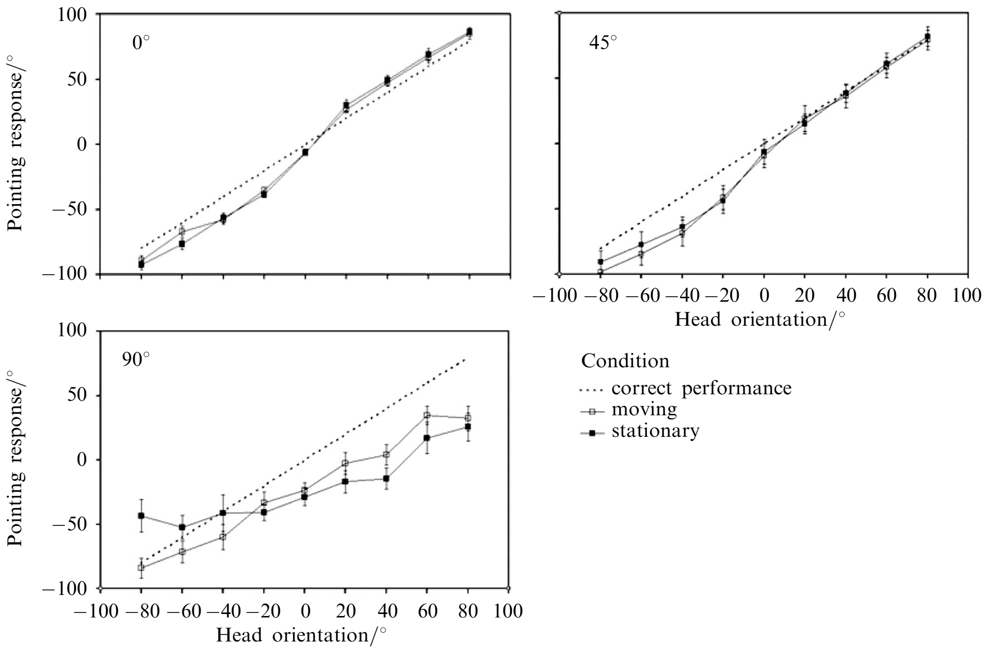


Figure 3. Mean pointing directions for ten participants' right field of view under the conditions 'moving' (visible head movement) and 'stationary' (static head position). The participant–looker distance was 2 m, and the error bars represent the standard errors of the mean.

[(1)] Except for 90° in the stationary condition, the data were well fit by linear functions. The r^2 values were 0.983, 0.972, and 0.538 for 0°, 45°, and 90° eccentricity in the stationary condition and 0.982, 0.975, and 0.821 for 0°, 45°, and 90° in the moving condition.

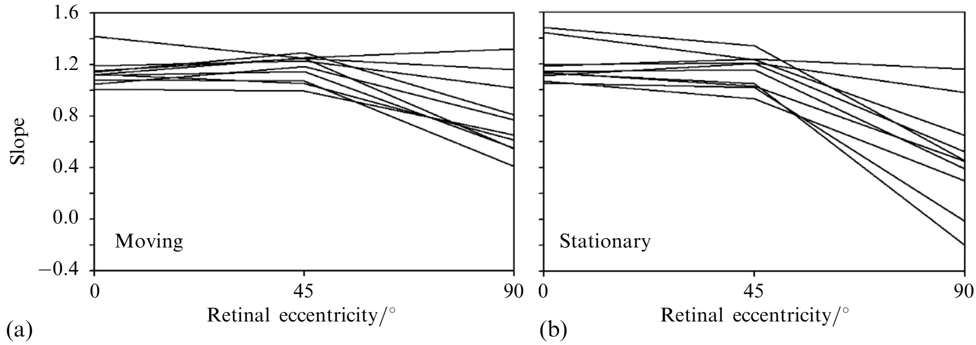


Figure 4. Slopes of the linear regression functions relating judged head orientation to physical head orientation, plotted separately for different retinal eccentricities and different participants. Movement of the looker's head was visible (a) or not visible (b).

at 90° eccentricity ($t_9 = 3.204$, $p = 0.011$). These results indicate that seeing the head move in the far periphery improves perception and performance when the visual information about head direction is degraded by the reduced visual acuity of peripheral vision. For a given retinal eccentricity, the visibility of the head is also determined by the angular size of the looker's head (which depends on the distance of the looker), the visual contrast between the looker's face and hair, and the visual contrast between the looker's head and the visual background. Indeed, Pusch (2001), using the same paradigm, found that increasing the distance of the looker from 2 m to 4 m did cause a reduction in head-sensing performance, as would be expected. It stands to reason that the additional information from viewing the head in motion will improve the perceiving of head direction whenever the visibility of the head is reduced for any of the aforementioned factors.

For 0° retinal eccentricity, there is overestimation of facing direction (ie slopes greater than 1.0), for both the moving ($t_9 = 4.024$, $p = 0.002$) and stationary ($t_9 = 4.184$, $p = 0.003$) conditions. The reason for this overestimation is unclear, but Anstis et al (1969) reported a similar result for judgments of eye gaze. There is also a slight bias (about 4°) for judging the facing direction toward the participants' right side (or, from the looker's perspective, to the left of the participant). Previous studies have shown minimal bias in judging the direction of mutual eye gaze when the participant views the looker foveally (Anstis et al 1969; Cline 1967; Gibson and Pick 1963). We are unable to say whether the slight bias observed here reflects the actual judgment of head direction or our method for measuring judged head direction.

Additionally, constant errors change as eccentricity increases. For 45° eccentricity, both for moving and stationary conditions, the overestimation bias for positive azimuths (when the looker is facing to the right and in front of the participant) disappears and the overestimation bias for negative azimuths increases. For 90° eccentricity, the two response functions have much shallower slopes than for 0° and 45°, perhaps reflecting 'regression to the mean' under uncertainty, with consequent changes in the constant errors. In particular, positive azimuths are now greatly underestimated.

Whether viewing stationary or moving stimuli, mean slopes for 0° and 45° viewing were quite close to 1.0 (see figure 4). This indicates that participants were able to use central and peripheral vision to reliably perceive changes in head direction, regardless of whether or not the looker's head was viewed while it was turning to face the next target direction. For 90° retinal eccentricity, which is close to the horizontal limit of the visual field for humans, slopes were considerably lower. Nevertheless, it is remarkable that the mean slope was still a high 0.79 (SE = 0.09) for moving-head viewing and 0.47 (SE = 0.13) for the stationary-head viewing.

In experiment 2 we are concerned with the psychophysics of perceiving eye gaze with peripheral vision; specifically, how sensitivity to variations in eye gaze depends upon both retinal eccentricity and viewing distance. Previous work indicates that, under foveal viewing conditions, gaze detection is quite good for viewing distances as large as 15 m (Watt et al 2007). However, performance is likely to be much more limited under peripheral viewing conditions. In a detailed analysis of the results from experiment 2 we explore whether sensitivity to eye gaze as a function of eccentricity and distance can be accounted for solely by the eye-gaze stimulus when scaled in terms of the spatial resolution threshold.

3 Experiment 2

3.1 *Method*

3.1.1 *Participants.* Eight graduate students at the University of California Santa Barbara were paid for their participation. All participants were verified to have at least 20/20 vision, as measured by Keystone orthoscope. Participation took approximately 2 h.

3.1.2 *Stimuli.* Four different lookers were digitally photographed with multiple eye-gaze directions, ranging from $-30°$ to $+30°$ azimuth in increments of 5°, where 0° eye gaze was straight at the camera (see figure 5). As a result, there were 13 photographs of each looker. In all cases, the looker's head faced the camera, with only the eye gaze varying. To ensure accurate gaze stimuli, lookers placed their head in a chin-rest and were instructed to fixate a horizontal bar, marked in the correct angular directions. Of the four lookers chosen, two were male, two were female, two had brown eyes, and two had blue eyes. Our use of photographs instead of live lookers allowed for more trials per participant (no time was needed for looker repositioning) and also allowed the experimenter to confirm that the lookers' heads always faced 0° (it is somewhat difficult to maintain a constant head orientation when gaze is deflected to the side). Because the eyes of the looker are nearly coplanar with the face, 3-D cues about gaze direction are minimal in natural situations when the face is viewed straight on, implying that real faces and pictures of faces are very similar as stimuli for gaze direction.

Figure 5. Examples of one looker with three different gaze eccentricities ($+30°$, 0°, and $-30°$ gazes are shown from left to right, respectively).

3.1.3 *Design.* Participants viewed full-colour photographs of the lookers on a video monitor (Gateway VX700 CRT; 33 cm horizontal $\times$ 25 cm vertical; 1024 pixels $\times$ 768 pixels). The photographs were viewed with seven different retinal eccentricities (0°, 1°, 2°, 4°, 8°, 12°, and 16°) and from two different distances (0.84 m and 3.0 m). For each retinal eccentricity and each viewing distance, participants judged looker eye-gaze direction in all 13 photographs of each of the four lookers. In total, each participant made 728 judgments of eye gaze. Viewing distance was blocked, and the order was determined randomly for each participant. For each viewing distance, retinal eccentricity was also blocked and presented in a random order. For each retinal eccentricity, looker eye gaze was randomized. All stimuli were viewed monocularly, with an eye patch used to cover the nonviewing eye. The viewing eye (left or right) was randomly varied between participants. Monocular viewing was used to eliminate binocular disparity cues signifying flatness of the video monitor, thus making the picture perceptually more similar to a real face.

3.1.4 *Procedure.* Participants sat directly in front of the video monitor displaying the digital pictures of the lookers. Positioned 42 cm in front of the monitor was a 2 m wide horizontal bar numbered from 0 to 50 (see figure 6). When a looker's photograph was displayed on the monitor, the participant was instructed to indicate the number on the bar to which the looker's eye gaze was directed. The participant did so by typing the number on a keyboard at desk level. Because the spatial relation between the image of the looker and the bar remained the same for the two different distances of the participant, the gaze of the looker's image was geometrically correct for both distances.

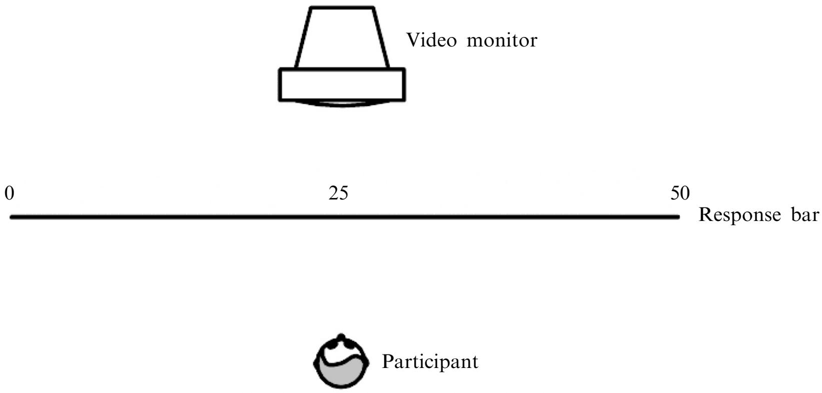


Figure 6. Plan view of the experimental setup showing the video monitor, the numbered response bar, and the participant's position when viewing stimuli from the near distance (0.84 m). The far distance (3 m) position is not shown.

Prior to viewing the stimuli, the participant's head was placed in a chin-rest. Additionally, participants were presented with a fixation point to ensure the correct retinal eccentricity when viewing the stimuli. The position of the fixation point (left or right of the monitor) depended on the viewing eye: for left eye viewing, the fixation point was placed to the left of the photograph; and for right eye viewing, the fixation point was placed to the right of the photograph. This was done to ensure that the image of the photograph always fell on the temporal hemiretina, thus avoiding the optic disk (blind spot) of the nasal hemiretina. Retinal eccentricity was measured as the angle between the fixation point and the looker's eye nearer the fixation point, with the participant's eye at the vertex.

When the participant was looking at the fixation point, he/she pressed a key to begin the next trial. Thus, the experiment was entirely self-paced. When a trial was initiated, the looker's photograph appeared on the monitor for 250 ms.[(2)] Participants were instructed to look at the fixation point during the stimulus exposure, after which the participant was free to move both gaze and head while responding.

[(2)] The stimulus presentation time in experiment 2 was shorter than in experiment 1. The shorter presentation time was chosen to prevent participants from attempting to fixate the looker. This was particularly important in experiment 2 because the retinal eccentricities tested were more closely spaced than they were in experiment 1.

3.2 *Results and discussion*

Figure 7 presents judged gaze direction as a function of physical gaze direction for both near and far viewing distances and for all seven retinal eccentricities, collapsing across the four lookers and the fixation direction of the participant (left and right). For each participant, looker face, fixation direction, retinal eccentricity, and viewing distance, performance was quantified by calculating the slope of the best-fitting linear function. A four-way, mixed-model ANOVA with terms for viewing distance (near or far), looker face (lookers 1–4), retinal eccentricity (0°, 1°, 2°, 4°, 8°, 12°, or 16°), and fixation direction (left or right) was performed on the slope data. The ANOVA revealed only these significant main effects: viewing distance ($F_{1,6} = 6.468$, $p = 0.044$, $\eta_p^2 = 0.52$) and retinal eccentricity ($F_{6,30} = 56.376$, $p < 0.001$, $\eta_p^2 = 0.90$). The only significant interaction was that between viewing distance and retinal eccentricity ($F_{6,36} = 8.516$, $p < 0.001$, $\eta_p^2 = 0.59$). Since looker face and fixation direction had no effect on performance, data are henceforth collapsed across these variables.

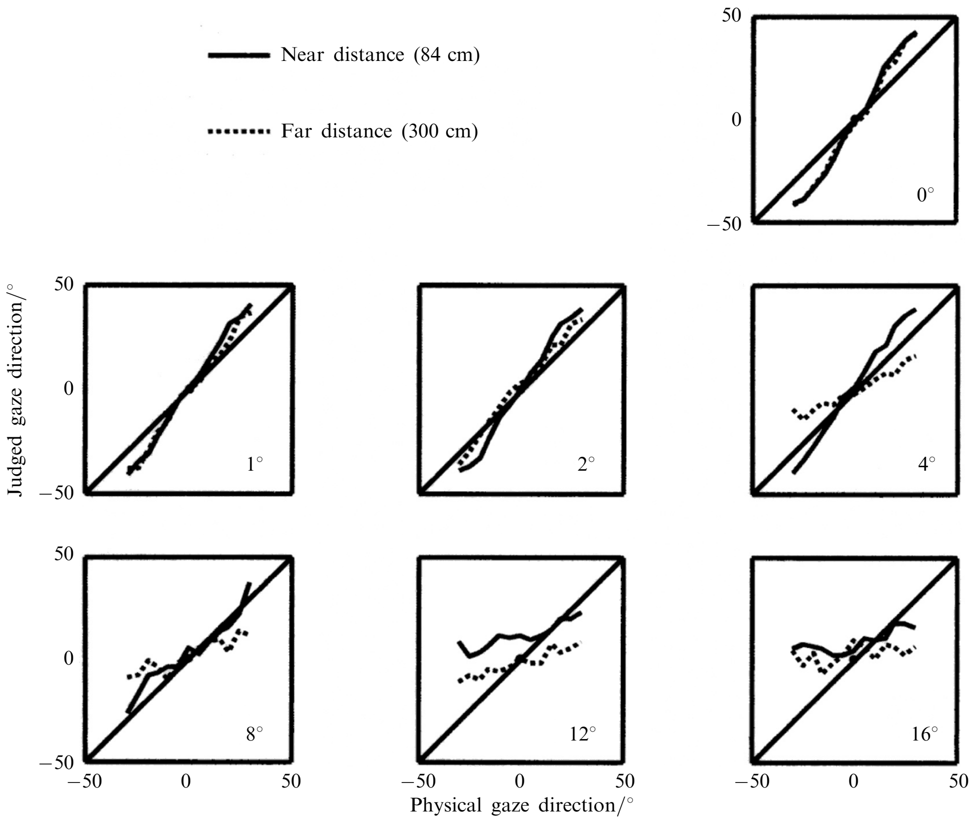


Figure 7. Mean judged gaze direction as a function of physical gaze direction for both near and far viewing distances and for all seven retinal eccentricities (0°, 1°, 2°, 4°, 8°, 12°, and 16°).

Figure 8 presents the mean slopes, averaged over participants, as a function of retinal eccentricity and viewing distance. Not shown are the slopes for 0° eccentricity, which were 1.54 (SE = 0.20) for near viewing and 1.49 (SE = 0.18) for far viewing. As retinal eccentricity increases, slopes decrease dramatically, indicating that the sensing of eye gaze worsens with small values of retinal eccentricity. The fall-off in performance occurs at a smaller retinal eccentricity for far viewing than for near viewing. This pattern is expected, since the visual angle of the stimulus is smaller under far viewing conditions. The mean visual angle of the lookers' eyes was 1.7° for near viewing and 0.5° for far viewing.

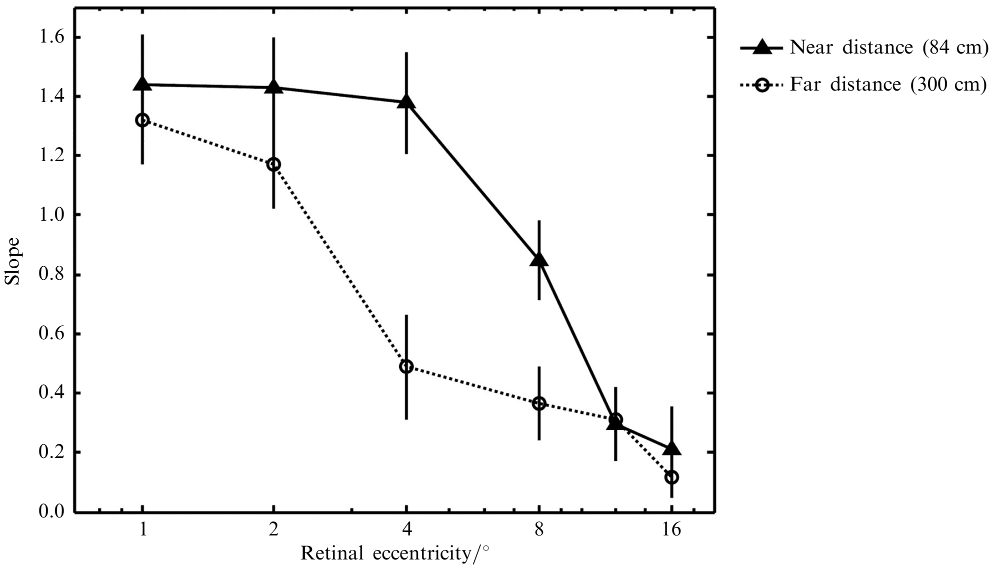


Figure 8. Mean slopes of the linear functions relating judged gaze direction to physical gaze direction, for both near and far viewing distances and for all of the retinal eccentricities except 0°. Error bars represent the standard errors of the mean.

Under foveal viewing, participants tended to overestimate eye-gaze direction (figure 7) for both positive and negative azimuths. For example, when the looker's gaze was diverted by 30°, participants estimated that the looker gaze was diverted by 40°. This was the case for both leftward and rightward looker gaze directions. This finding replicates the results of Anstis et al (1969) and our experiment 1. Anstis et al (1969) also found the same effect using a simulated eyeball (a plastic sphere with an iris and pupil, of the same dimensions as a typical eye).

Because the perception of eye gaze falls off with both retinal eccentricity and distance of the looker, it is possible that both effects can be understood in terms of the limiting effects of visual acuity, which is the reciprocal of the spatial threshold. To test this hypothesis, we began with extant data reporting visual acuity for different retinal eccentricities. Wertheim (1894; reprinted in Westheimer 1987) measured the minimum angle of resolution (MAR) at retinal eccentricities out to 30° in a dark room, using high-contrast stimuli (black and white stripes). MAR, a traditional measure of visual acuity, is the smallest resolvable width of one black (or white) stripe in the black-and-white striped stimulus. Although Wertheim did not test all of the retinal eccentricities that we used in experiment 2, the relationship between MAR and retinal eccentricity estimated from his data is very well described by a linear function with slope 0.0074 and intercept of 0.0151 ($r^2 = 0.99$). MAR data for all eccentricities tested in experiment 2 were estimated with this function. The resulting estimated MARs for eccentricities of 0°, 1°, 2°, 4°, 8°, 12°, and 16° were 0.015°, 0.023°, 0.030°, 0.045°, 0.074°, 0.104°, and 0.134°, respectively.

In order to test the hypothesis that the effects of retinal eccentricity and viewing distance on eye-gaze judgments could be due to reduced acuity in peripheral vision, we used the MAR values estimated from Wertheim (1894) to compute the number of 'resolution units' of the eye stimulus from experiment 2. Thus, when viewing the eye-gaze stimulus with a retinal eccentricity of 8°, the image of the looker's eye (24 mm in diameter) subtended 6.2 resolution units for the far distance and 22.1 resolution units for the near distance. If performance in experiment 2 was worse for far viewing solely because the stimuli of smaller angular size were more limited by the reduced visual acuity of peripheral vision, then performance in judging eye-gaze direction should be completely predicted by the number of resolution units in each condition. In figure 9 the slope values from figure 8 are plotted as a function of the number of resolution units. Also shown are the best-fitting probit functions. The prediction is not well supported, for the near and far data fall on clearly different curves. Thus, although the sensing of eye gaze under the conditions of experiment 2 is surely limited by the visual acuity of peripheral vision, visual acuity as measured by the targets of Wertheim does not completely account for the differences between judgments at near and far viewing distances, somewhat limiting the generality of the findings. However, it is well known that performance on a variety of visual tasks in peripheral vision is limited by 'crowding' (Pelli et al 2004)—visual interference produced by nearby visual stimuli. Because the MAR data reported by Wertheim were obtained for visual targets in isolation, they do not reflect crowding effects. Had the MAR data reported by Wertheim been collected within the visual context of the eye-gaze task, it is likely that the MAR values for far viewing would be selectively increased relative to those for near viewing, thus bringing the curves for near and far viewing closer together.

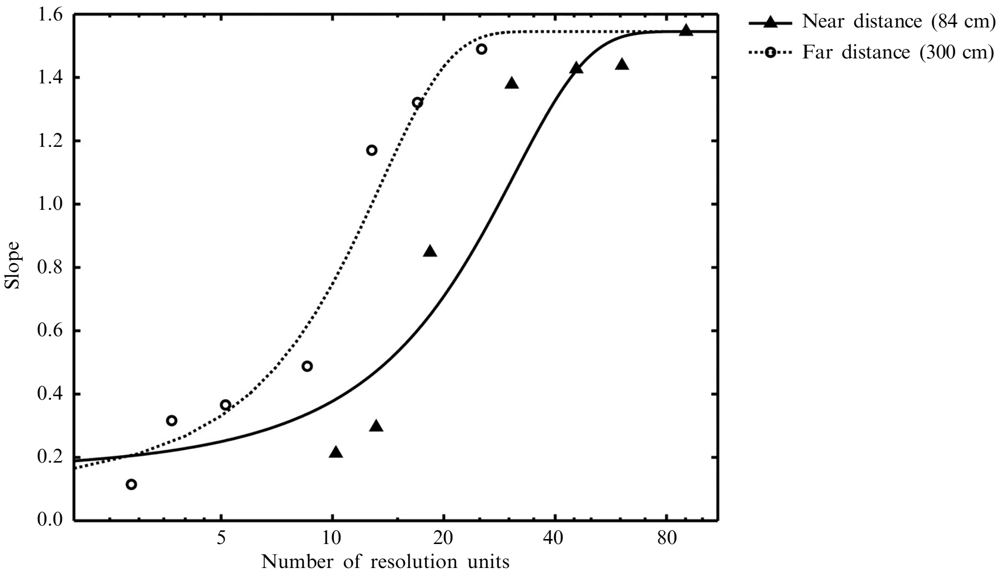


Figure 9. Mean slopes of the linear functions relating judged gaze direction and physical gaze direction plotted against the number of resolution units in the eye stimulus, with best-fitting probit functions.

4 General discussion

These experiments establish two important psychophysical results. First, the sensing of head direction, which is usually a good indicator of the looker's attentional focus, is effective all the way out to 90° retinal eccentricity when the looker is within 2 m, a range within which many social interactions take place (ie the range of social distance specified by Hall 1966); sensing of head orientation near the limits of peripheral vision was improved when the participants were able to view the looker changing head orientation from one trial to the next. Second, the sensing of eye gaze, which is an even more reliable indicator of the looker's attentional focus, is only good for central vision (within 4° retinal eccentricity) at the same social distance. This means that a perceiver under these conditions needs to fixate the near vicinity of the looker's face in order to sense the looker's direction of eye gaze. Because the perception of eye gaze worsens with both increasing viewing distance and increasing retinal eccentricity, it is reasonable to suppose that eye-gaze perception is limited by the size of the eye-gaze stimulus when measured in terms of the angular spatial threshold (reciprocal of visual acuity). However, analysis of the data showed that when the size of the eye-gaze stimulus is expressed in number of resolution units, performance is not the same for near and far viewing. However, because crowding (Pelli et al 2004) in peripheral vision is another limiting factor besides acuity, it is still possible that limits on eye-gaze perception across different visual contexts might be accounted for solely in terms of low-level perceptual processing.

Both eye and head movements are used during conversation to provide a number of conversational cues unrelated to attention, such as emotional emphasis and signaling turn taking (Kendon 1967). However, neither head direction nor eye-gaze direction is an inviolable indicator of the direction of a person's attentional focus. The eyes are almost always directed at points of interest, but a person can willfully direct attention to targets that are not being fixated. There is a much greater decoupling between head direction and attentional focus, for one can maintain fixation on the target of interest while the head is turned. However, because of the physical discomfort of prolonged and large deviations of the eyes from the straight-ahead position of the head, people usually turn their heads into alignment with the eyes shortly after fixating targets of interest.

The two primary psychophysical results of these experiments elucidate some of the dynamics of social interaction based on one interactant's sensing of another's attentional focus. The two results confirm that there is a huge difference in accessibility of the social signals provided by head direction and eye gaze. Because an interactant can direct the eyes in a direction different from that of the head, an interactant can take advantage of this difference in cue accessibility to conceal his/her focus of attention from others in both dyadic and triadic interactions. For example, person A wishing to 'steal a glance' at the body part of person B can do so by fixating the part of interest while keeping the head stationary. Because person B will perceive the attentional focus of A only when fixating A's eyes, stealing a glance is often successful. Concealment also occurs in triadic interactions. If A wishes to engage in surreptitious signaling with B by way of eye gaze (eg 'rolling the eyes'), A will be careful not to turn the head toward B lest C senses the interaction. At the same time, A and B can monitor C's focus of attention using their peripheral vision, under the assumption that C is attending in the direction of his/her head. Obviously, if C is surreptitiously monitoring the interactions of A and B by way of eye gaze different from his/her head direction, the surreptitious communication between A and C can be intercepted. Additionally, head orientation tends to follow eye gaze even when one actively attempts to maintain head stability (Doherty and Anderson 2001). Although surreptitious eye movements may go unnoticed, these accompanying and unintentional head rotations may not.

This research has implications for the effectiveness of telecommunication systems designed for video-teleconferencing and collaborative work involving small groups. Viewing with peripheral vision is probably more pervasive in small group interactions than is widely realized. Besides the above-mentioned surreptitious signaling within a group, collaborative work and other forms of cooperative group activity require an appreciation of the attentional foci of the different participants. For example, the person who is discussing an object of focus can use peripheral vision to monitor whether other group participants are properly engaged. Such monitoring surely promotes effective and efficient group interaction. Any technology used to support interaction between remotely situated group members will be most effective when all of the social signals for joint attention and nonverbal interaction are provided for. In a review of the literature comparing current computer-mediated communication systems, Whittaker (2002) concluded that augmenting verbal communication with visual representations of the others does not improve task performance or the subjective communication experience. Because many head-mounted displays used in virtual reality today have horizontal fields of view of 80° or less, such displays surely filter out some of the important social signals for natural and effective group interaction. Perhaps as the technology improves, allowing for wider visual fields of view, the availability of social signals will increase, with a consequent increase in the effectiveness of social interaction.

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