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The effect of head turn on the perception of gaze

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ABSTRACT

When subjects viewed straight and turned eyes that were isolated singly or in pairs from a head that was straight or turned, they underestimated their true direction of gaze. They also underestimated the direction of head turn when both eyes were closed. However, the judged direction of gaze was improved when the eyes were layered against the heads. Judged direction of averted gaze was primarily based on the abducting eye. The effect that the deviation between an eye's optical axis and its true direction of gaze (angle kappa) has on its judged direction of gaze is discussed.

1. Introduction

Many social and cognitive functions in humans depend on the ability to quickly and accurately judge another person's direction of gaze. Primarily, gaze is important as a form of intended and unintended communication (Argyle & Cook, 1976; Gale & Monk, 2000; Kendon, 1967). Langton and his colleagues (Langton, 2000; Langton, Honeyman, & Tessler, 2004; Langton, Watt, & Bruce, 2000) have reported evidence that the perceived direction of gaze is fast, automatic, and uses multiple cues which are processed at both lower and higher levels by dedicated brain mechanisms. Perrett, Hietanen, Oram, and Benson (1992) have found cells in the superior temporal sulcus (STS) of the temporal lobe of the macaque monkey that respond to the direction in which another monkey is looking, which also suggests a modular mechanism for this function. Even though humans cannot be investigated in the same way, there is reason to believe that their processing of gaze information may be similar because humans who have damage to the equivalent area also have impaired gaze-recognition, even though they may retain intact face recognition abilities.

Among primates the contrast between the sclera and iris is uniquely high (Kobayashi & Kohshima, 1997; Ricciardelli, Baylis, & Driver, 2000). However, even though this allows the ocular features to be easily seen, it is still not clear how they are used to judge where a person is looking. These cues may superficially appear to be trivial, but their use in the perception of gaze is actually complex.

Wollaston (1824) was the first to publish the suggestion that the perception of gaze involves complex cues. He used the images that are reproduced in Fig. 1 to demonstrate that judgment of gaze direction is not based solely on the estimation of where the irises are located within the lid aperture, but also on whether or not the head is turned. Although, the eyes on the two heads in Fig. 1 are identical, the eyes on the image to the right seem to be making eye contact with the observer, whereas the right head turn in the image to the left makes the eyes appear to be looking to the observer's right. This is now referred to as the "Wollaston effect," in which the perceived gaze direction of the same or similar eyes layered against a head which is turned relative to the first is drawn toward the direction of turn.

It was not until more than 100 years later that Gibson and Pick (1963) published the first study that experimentally measured the effect that head turn has on the perceived direction of gaze. In their study, when observers viewed a live model from 200 cm with the model's head turned 30° to the observers' left, the observers felt that they were being directly looked at when the model was actually looking at their left ear. A significant body of subsequent research has now studied this head turn effect.

Cline (1967) used a live model with a 30° and a 0° head turn similar to the images shown in Fig. 5. Cline reported that a straight head with straight gaze had a very small average error and standard deviation (SD) but they became much larger when gaze was directed up to 12° to the right or left of straight ahead. When the head was turned 30°, gaze 10° to the same side as the head turn also resulted in a very small average error, but gaze 10° to the opposite side resulted in a much larger average error. However, the SD increased from that for the straight head by about the same

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Fig. 1. Wollaston's drawings demonstrate the qualitative effect of head turn on the perceived direction of gaze. The eyes in both the right and left faces are nearly identical, but the head turn makes the two sets of eyes appear to be looking in different directions.

amount whether gaze was directed to the right or to the left of the observers. (This was in contrast to Gibson and Pick (1963) who inexplicably found low thresholds similar to those found when the model gazed directly at the bridge of the observer's nose.) When the eyes and head were directed identically toward 10° to the right or left of the observers, both average errors and SD tended to be small. There is some confusion in the literature because Cline's Table 2 may have mixed up data for right and left (Anstis, Mayhew, & Morley, 1969; von Cranach & Ellgring, 1973). Our above interpretation is based on Cline's claim that his results agree with Gibson and Pick (1963).

Anstis et al. (1969) studied the perceived direction of gaze when observers viewed live models and models that were displayed on a TV screen; both at a distance of 84 cm, while the models gazed at different locations along a horizontal scale that was located half way between the model and observer. This study confirmed the shift in perceived direction of gaze associated with direction of a head turn found by Gibson and Pick (1963) and Cline (1967). In agreement with Cline, judgment of gaze in the direction of a 30° head turn resulted in smaller errors than when gaze was turned against the direction of the head turn, and was close to the errors produced when the head was straight. They also reported a new effect, that the direction of perceived gaze was overestimated for all side gaze from straight ahead.

Maruyama and Endo (1983) and a similar study by Maruyama, Endo, and Sakurai (1985) used faces which were drawn as circles with cutout elliptical eye apertures behind which irises drawn on a paper slider could be adjusted by their observers to where they felt they were being gazed at. For those circles that represented a turned face, the apertures were offset toward the direction of head turn but the faces were still circular. They confirmed that the perceived direction of gaze was between the direction in which the eyes were gazing and the direction of the head turn and described this as the head "towing" the perceived direction of the eyes from their true direction. The effect was greatest for large discrepancies between gaze direction for eyes without head and head without irises. They also reported that the perceived head orientation was not affected by the direction of gaze.

Since head turn influences the perceived direction of gaze it is important to know how head turn itself is perceived. Several studies have measured head turn thresholds and have determined which features of the head influence them. Wilson, Wilkinson, Lin, and Castillo (2000) had observers view the imaged heads of three models on a computer monitor from 125 cm in which the heads were incrementally deviated from the base angles of 0°, 15°, and 30°. In each trial the observers indicated which of the stimuli was farthest from straight ahead. For both the 0° and 15° head orientations the threshold head turn was about 2°, but it was about 5° for the 30° head turn. The thresholds for head turn were not significantly different when using the head contour or internal features alone, including the nose alone, than when using the entire head. However, as the head angle approached 30°, the nose angle became more important than head contour. They found no significant effect with changes in spatial frequency or with differences in head size.

Langton et al. (2004) also reported that both nose and symmetry of head contour were used to determine the perceived direction of head turn, but they went beyond Wilson et al. (2000) by studying whether those cues were also the ones that were used to determine gaze direction. Their observers viewed eyes which were either directed toward them or were angled slightly to their left or to their right and judged whether the gaze was direct or averted. The head outline alone or the nose angle was oriented in the same (congruent) or in the opposite (incongruent) direction to that of the eyes. They confirmed the effect of head turn on gaze perception and found that the observers' ability to discriminate direct from averted gaze was significantly better in congruent than in both the incongruent and absent conditions. Moreover, performance was significantly poorer in the incongruent condition than in the absent condition. When only the outline of the head plus eyes was used, whether congruent, incongruent, or absent, they found that head contour alone was sufficient to induce a Wollaston-like effect. When they re-centered the eyes to eliminate their lateral displacement with turn of the head outline, the shape of the head profile was still sufficient to influence the perception of gaze direction. Deviation of nose angle alone influenced perception of gaze direction although the effect was smaller than the head-contour effect. Again, an incongruent nose angle made it more difficult for subjects to distinguish direct from averted gaze.

Todorovic (2006) studied the interaction of head and eye turn by using computer-generated heads in which head orientation and iris eccentricity were varied as a percent deviation from symmetry rather than angle of deviation. When translated to degrees the head turn threshold was about 1.8°, which is close to the 1.9° reported by Wilson et al. (2000).

Todorovic (2009) argued that the projected view of the eyes, nose, and mouth, which he calls face eccentricity, is distinct from other cues such as head contour and nose angle. Because so many other cues are present in a natural face, he isolated eccentricity as a cue by using oval line-drawn faces, which contained line-drawn eyes, nose and mouth that were offset from the center of the face by various percents. He found that eccentricity alone was a powerful cue for the perceived direction of gaze. In order to maintain the perception of fixed gaze, every 1% shift of the facial features from centered, corresponded to an iris shift in the lid apertures of 0.21–0.53%, depending on the method that he used to test this.

Variables other than eye and head turn can also influence the judged direction of gaze. For instance, Ando showed that a darkening of the sclera on the same side of each eye results in an apparent deviation of both eyes in the direction of the darkening, the so-called "bloodshot effect" (Ando, 2002, 2003, 2004; Ando & Osaka, 1998). Perceived direction of gaze may similarly be influenced by an asymmetry in the illumination of the two sides of the face. Noll (1976) reported that, when his models gazed at the camera, their images were judged to be gazing about 3° to the side, and he suggested that this was because the opposite side of his models' faces were in light shadow so that their heads might appear to be somewhat turned. Troje and Siebeck (1998) subsequently did a controlled study which showed how shading one side of a face can cause the head to appear to rotate in a direction opposite to the shifted direction of the light source. In addition, a model's facial expression (such as a smile), and extraneous objects close to a model have been shown to capture the perceived direction of gaze (Gamer & Hecht, 2007; Ganel, Goshen-Gottstein, & Goodale, 2005; Lobmaier, Fischer, & Schwaninger, 2006).

Another variable, which has been largely neglected, is angle kappa (κ). Kappa is the angle between the line of sight (the line from the object of regard to the center or the pupil) and the pupillary axis (the line directed from the center of curvature of the cornea through the center of the pupil) (Fig. 2). The anterior–posterior axis of symmetry in an optical instrument is the optical axis, which is the line that goes through the centers of curvature of all of the optical surfaces, and it is the direction toward which the instrument is aimed. In the human eye this axis of symmetry can only be judged by the outward appearance of the eye, and the best estimate for this would be the line perpendicular to the center of the iris/pupil, i.e., the pupillary axis. However, unlike most optical instruments, the eye has the most acute part of its image sensor (the fovea of the retina) located about 5° temporal to the optical axis. This angle is referred to as angle kappa, which is considered to be positive in the above case (Goss & West, 2002). Kappa varies between individuals but is generally symmetrical between the two eyes and positive, meaning that the pupillary axis is usually aimed to the temporal side of the object being fixated (Emsley, 1963; Giovanni, Siracusano, & Cusmano, 1988).

Since the pupillary axis is an estimate of the optical axis of the eye, and therefore the direction in which an eye is directed, angle kappa will cause a deviation of the line of sight from the eye's axis of symmetry. Thus a positive angle kappa of a few degrees may cause the eyes to appear to be exotropic (deviated outward) in straight ahead gaze (Griffin & Grisham, 1995; Kanski, 2007; von Noorden, 1996). The effect of a typical angle kappa is not trivial. For instance, if a gazer's eye had an angle kappa of +5°, the apparent displacement of gaze at 100 cm would be 8.7 cm and, at that distance, it could displace monocular gaze entirely off of an observer's face. It remains to be tested whether observers perceive another person's direction of gaze as the eye's axis of symmetry, or whether they may take the average angle kappa into account.

Since the perceived direction of gaze is changed by a head turn even when the location of the irises within the lid apertures remains the same (the Wollaston effect), the perceived direction of gaze must depend on head turn as well as eye turn. Then any limitation in the accuracy with which the direction of a head turn can be detected should also limit an observer's ability to determine the direction of gaze. The cues that have been proposed to be used to assess head turn are: the deviation of the profile line or nose from the midline of the face; the deviation of head shape from bilateral symmetry; the lateral displacement of the two eyes from the center of the head contour; and a decrease in the distance between the two eyes due to the horizontal foreshortening of the face (Troje & Siebeck, 1998; Wilson et al., 2000). However, Wilson et al. immediately rejected the last cue listed on the basis that any change in inter-ocular distance would be too small to be detected. Also, cues supplied by the mouth and chin may not be necessary since Cline (1967) found that gaze perception was unchanged when the lower half of his model's face was covered.

Some of the studies reviewed above used grey scale images of variable true-to-life detail, such as schematic or computer-generated heads that were often displayed smaller than life size. These images are useful to obtain qualitative information because they use simplified features that isolate various cues to gaze. In most studies these images were viewed with both of the image's eyes open and postured for a distant target, so that potential differences in gaze between the two eyes were not studied. In our study we took the opposite tack. We used photographic images in order to gain information on the perceived direction of natural gaze when all of the complex details of a real head were present. We digitally photographed a live model to acquire images from the same distance at which they were to be displayed, and that had face-on illumination whether her head was turned or straight head. This allowed us to produce color images that displayed natural head turn, size, distance, perspective, shadow, angle kappa, and ocular convergence. We then presented these images to observers, with the model's eyes viewed separately or together, in order to determine how eye and head turn, alone and in combination, affected our observers' judgment of the model's direction of gaze.

2. Method

This project was reviewed and approved by our university Institutional Review Board and all subjects gave written consent.

2.1. Participants (model)

One 24-year-old, brown-eyed female subject who had a 64 mm distance between the centers of her irises served as our model. She

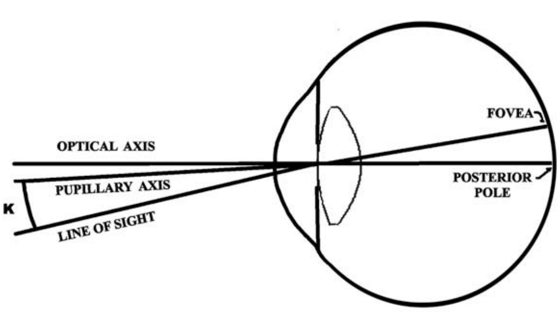

Fig. 2. Angle kappa and the axes of the eye. The gazer's right eye is drawn in horizontal cross section as viewed from above. The optical axis is the line that most nearly goes through the centers of curvature of all of the refractive surfaces of the eye and intersects the retina at the posterior pole. The best estimate of the optical axis when the eye is viewed from the outside is the pupillary axis, which is the line that goes through both the center of the pupil and the center of curvature of the cornea (i.e., it is perpendicular to the corneal surface). The line of sight is the line from the object being fixated by the eye that goes through the center of the pupil, and after all refractions intersects the retina at the fovea. Kappa is the angle between the pupillary axis and the line of sight. It is often symmetrical between the two eyes and positive, meaning that the line of sight is nasal to the pupillary axis.

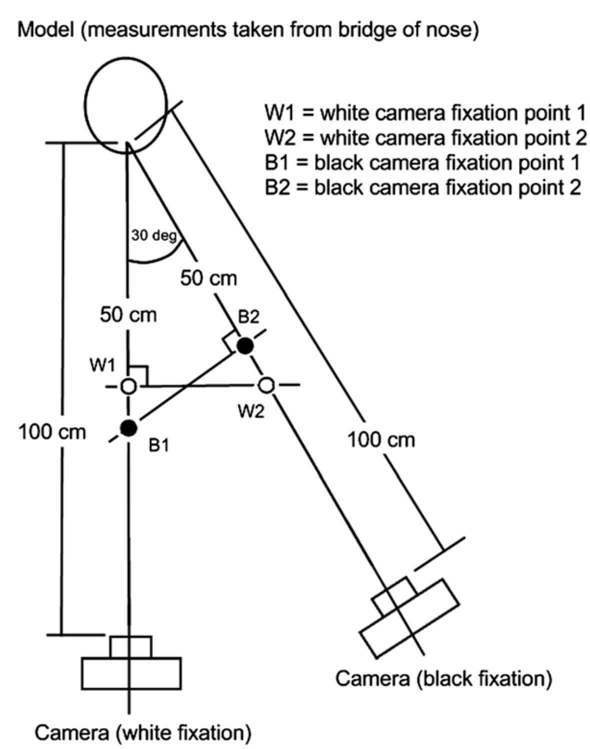

Fig. 3. The setup used to photograph the model as viewed from above. Camera #1 imaged the front of the model while camera #2 imaged the model 30° to the observer's right.

had uncorrected visual acuity of 20/20 at 50 cm in both right and left eyes and had stereo acuity of 40″ or better at near.

2.2. Apparatus (model)

We used the apparatus described in West, Salmon, and Sawyer (2008) to measure angle kappa for each of our model's eyes. The pupillary axis of the eye to the right was deviated 1.83° to the right of the line of sight, and the pupillary axis of the eye to the left was deviated 0.46° to the left of the line of sight. This gave a total of 2.29° outward deviation between the two eyes. We did not use Photoshop to simulate an angle kappa of zero as was done in a previous study (Stuteville, King, & West, 2007) because a positive angle kappa presents the most common ocular appearance and it allowed us to determine its influence on the perceived direction of gaze.

Next we seated our model in front of a black background and illuminated her with standard fluorescent ceiling panels mounted above and in front of her on her midsagittal plane. We then photographed her head with two Kodak C613 6.1 mega pixel cameras with a zoomed focal length of 108 mm. At that focal length we measured the image distortion across our model's face to be less than 0.5%. The cameras were mounted on tripods 100 cm away from the bridge of her nose. The first camera (camera 1) was located straight ahead of the model while the second camera (camera 2) was placed at a 30° angle to the model's left. Therefore, the images from the second camera showed the model with her head turned 30° to the observer's left (see Fig. 3). This also ensured that the illumination was kept perpendicular to the face plane regardless of head turn by keeping the head and illumination fixed while capturing images of the subject from the two camera angles. This avoided any bias that might result from asymmetric shadowing of the face and eyes.

We placed a white bead and a black bead (mounted on vertical wires) between each camera and the model (Fig. 3). The beads were used as fixation targets to direct the angle of the models gaze to 0° and 30° to her left. The cameras were aligned so that the beads were centered on the bridge of the model's nose, which ensured that the cameras were 30° apart. For the straight-ahead camera, the white bead was placed 50 cm and the black bead 57.7 cm from the model. For the camera located 30° to the model's left, the black bead was placed 50 cm and the white bead 57.7 cm from the model. This ensured that the point in the field of view 30° to the side was perpendicular to the line between each camera and the bridge of the nose. The black bead was placed 1 cm higher than the white bead so that the model's view of one bead was not obstructed by the other bead.

Images from the camera that was straight in front of the model showed gaze directed toward the white beads while images from the camera that was 30° to the side showed gaze directed toward the black beads.

2.3. Procedure (model)

The model was instructed to look at the white bead directly in front of her and the two cameras simultaneously took a picture. The model was then instructed to look at the black bead directly in front of her and both cameras again took a picture. The model then successively looked at the white and black beads located 30° to her left as the two cameras again took pictures. Finally both cameras

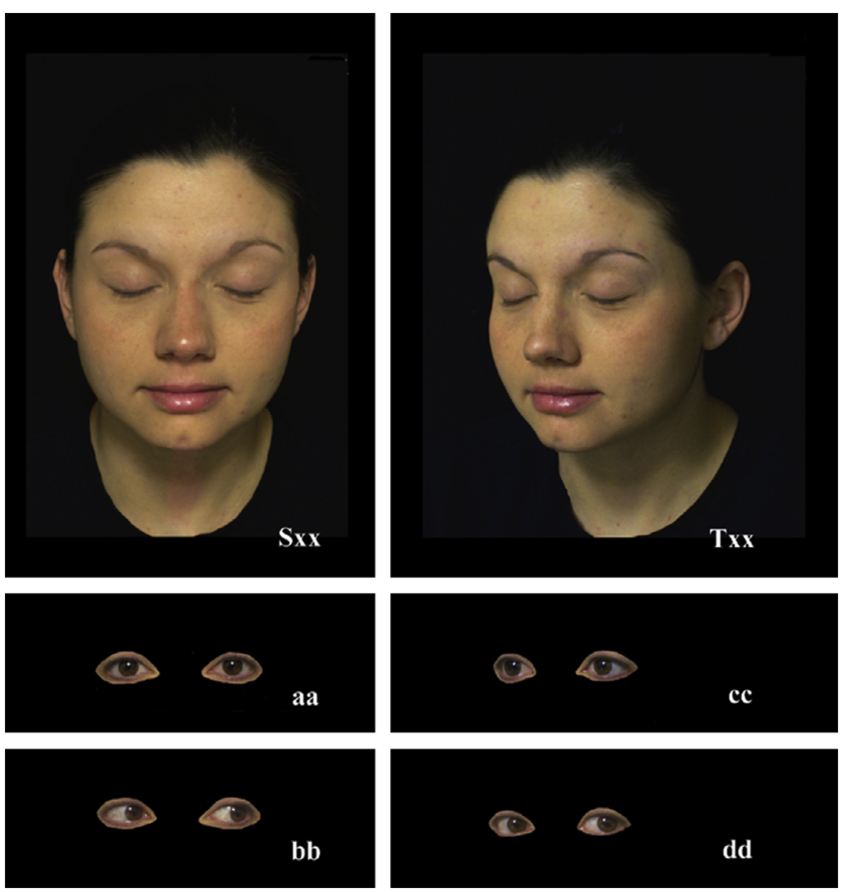

Fig. 4. Images of the heads with eyes closed and images of the isolated eyes that were presented to the observers. Not shown are the images in which the right or left eyes were displayed alone. These images were also used to construct the images in Figs. 5 and 6.

took a picture with the model's eyes closed and with the beads removed so that the beads could be edited out of the final images and the lids could be added. The pictures were taken as quickly as possible while the model held her head as still as possible.

We then realigned the model's head and repeated the above sequence eleven more times in order to acquire enough images so that we could select a series for which close inspection with Photoshop showed that her head was directed straight toward the central camera and that her head had not moved between image acquisitions.

We used Photoshop to alter the straight and turned images of the model's head. First the fixation beads were eliminated from the images by superimposing the corresponding areas of the model's face taken without the fixation beads. Then the eyes in different directions of gaze were layered against those images. The resultant images, some including only the cropped eyes, are shown in Fig. 4. The photoshopped heads with both of the model's eyes visible are shown in Figs. 5 and 6. Not shown in the figures, images were also generated with the right or the left lid closed. This resulted in 38 images. All of the images were then flipped right–left in order to control for observer motor biases for right vs. left. This resulted in a total of 76 different images.

2.4. Participants (observers)

Twenty optometry students between the ages of 21 and 35 years, 11 females and nine males, volunteered to be participants. All had at least 20/20 corrected visual acuity at both 100 cm and at 50 cm. These subjects served as observers who viewed images of the model on a computer screen and indicated where they perceived the model to be looking, or if both of her eyes were closed, where they perceived her head to be pointed.

2.5. Procedure (observers)

A 20-in. LCD monitor (1280 × 1024 pixel resolution) masked to 36 × 27 cm displayed life size images of the model at the model's previous location. The observers were seated so that their eyes were located 1 m from the monitor at the previous location of the central camera were they individually viewed the images.

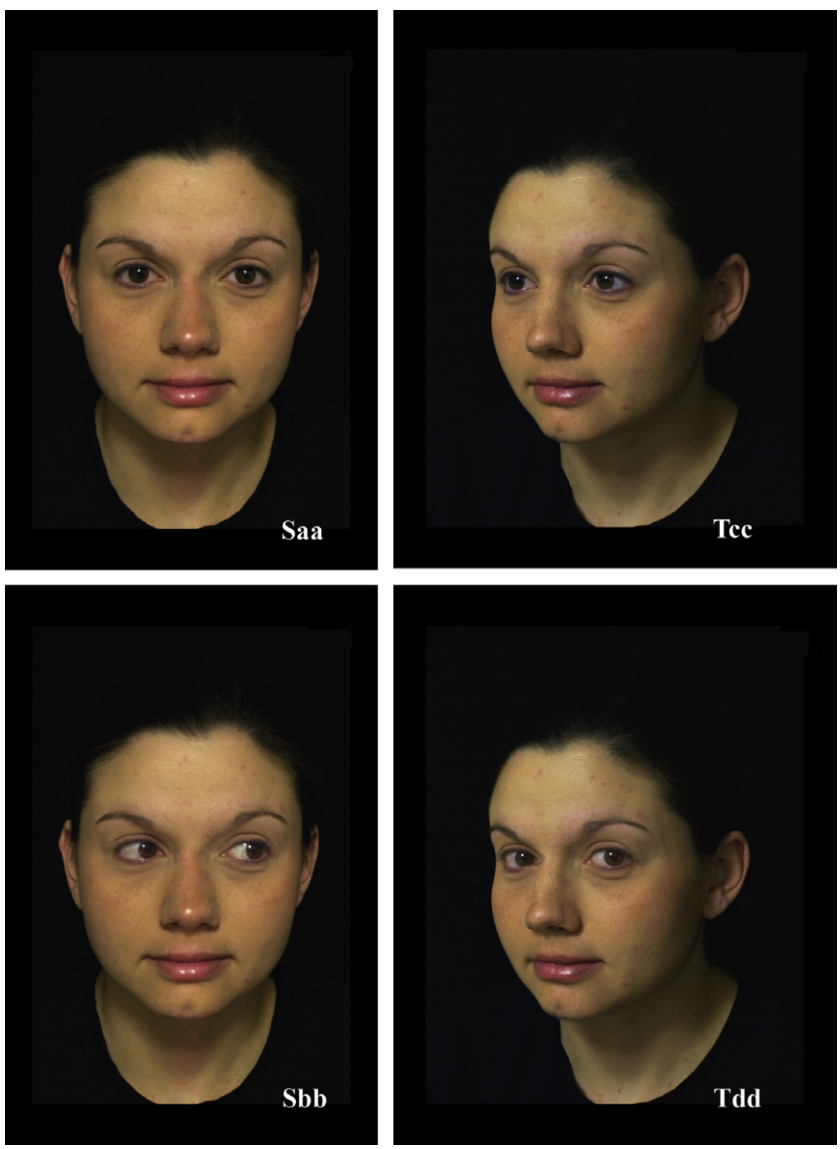

Fig. 5. Images of the straight and turned heads layered with congruent eyes that were presented to the observers. Not shown are the images in which the right or left eyes were closed.

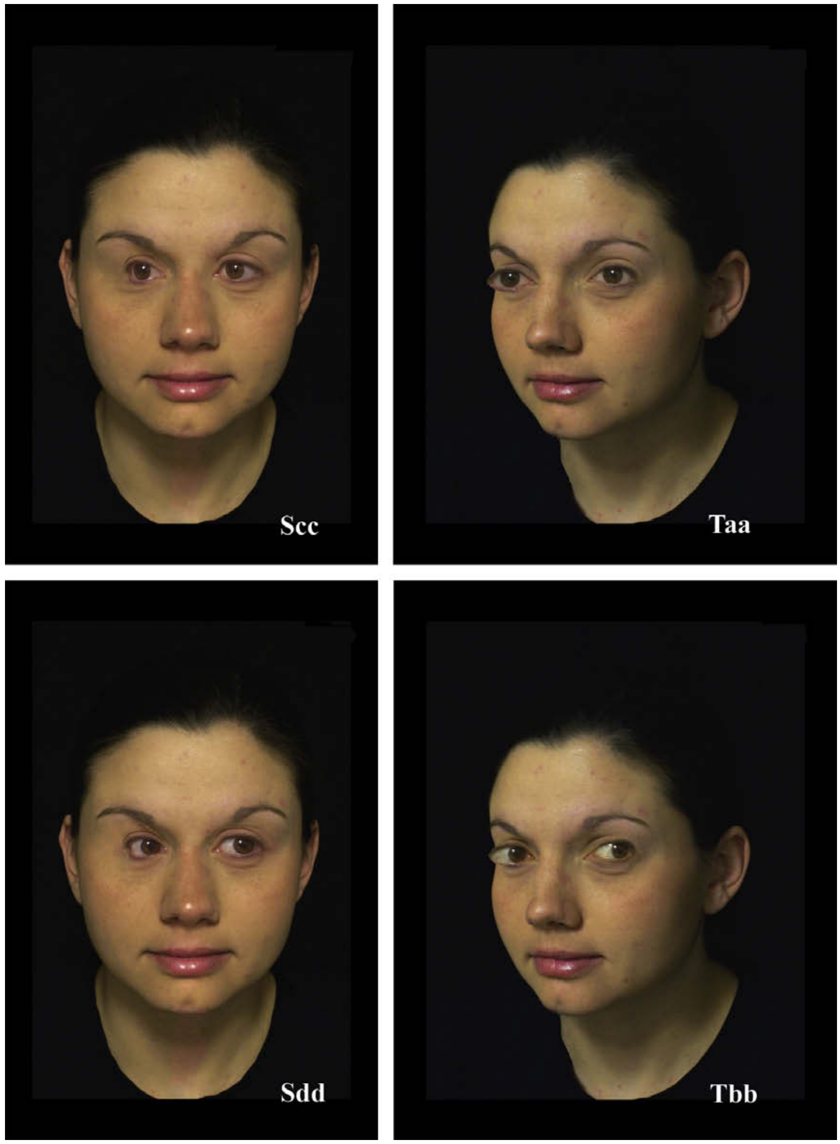

Fig. 6. Images of the straight and turned heads layered with incongruent eyes that were presented to the observers. Not shown are the images in which the right or left eyes were closed.

Viewing was done monocularly through a 35 mm diameter thin metal loop while the other eye was patched. The wire loop ensured that the distance and angle of observation were held constant. Monocular viewing was used to fix the egocenters of the observers to the metal loop. Otherwise, the egocenter, which would vary between observers, could be at any location between the two eyes (Howard & Templeton, 1966; Porac & Coren, 1986).

The observers viewed the images of the model's head and/or eyes and for each image they slid a fixation bead along an optical bench rail to the location where they judged the model's eye(s) were looking directly at the bead or, if both eyes were closed, where they judged her head was pointed. The rail was oriented parallel to the plane of the monitor at a distance of 50 cm from the monitor so that the beads ran along the same line upon which they were located when the images were acquired. The observers were patched so that half of them viewed the images with their right eye first while the other half viewed the images with their left eye first. Then each observer viewed all of the images again with their previously patched eye.

The 0.0 cm midpoint of the rail which carried the beads was aligned with the center of the images on the monitor, making 0.0 cm the reference point for straight ahead gaze. After each image was judged, the bead was placed back to the 0.0 cm location before the next image was displayed. Measurements were recorded to the nearest 0.5 cm.

The 76 images of the model were presented to the observers against a black background and were randomized within each of three groups. The first group of images presented individually cropped right and left eyes. The second group of images presented cropped pairs of eyes. And, finally, a third group of images presented right eyes, left eyes, both eyes, and closed eyes layered against both straight and turned heads. We used this sequence of presentation in order to analyze how the successive incremental addition of cues changed the perception of gaze direction. All groups of images were then repeated, which resulted in a total of 152 images. The sessions took between 40–55 min per observer.

3. Results

The images were presented flipped as well as un-flipped in order to counterbalance any motor bias that the observers might have had for right vs. left responses. During analysis the flipped images were un-flipped and combined with their un-flipped counterparts. This allowed us to show all head turns as turned to the observer's left. All head and eye directions referred to as right or left are relative to the *observer's* right or left.

Figs. 7–9 show bar graphs which compare the judged direction of gaze and head turn in degrees for each stimulus image. The image abbreviations correspond to those in Figs. 4–6. For example, the abbreviation Saa refers to a straight head with both eyes visible, while Sxa (not shown) refers to a straight head with the eye to the left of the observer closed. Relative to the observer, the true direction of the head turn was either 0.0° or −30° and the true direction of the eye turn was either −30°, 0°, or +30°. (Negative numbers represent locations to the observer's left, and positive numbers to the observer's right.)

Table 1 presents the mean deviations in degrees of the judged directions of gaze from straight ahead and summarizes their statistical significance. A non-parametric Friedman ANOVA by ranks was run on each triplet of right, left, and both eyes visible for each image in Figs. 4–6 in order to determine which triplet sets contained unequal ranks. For those triplets that revealed significant differences at $p < 0.05$ a sign test was run on each of the three possible pairings to determine which pairs were significantly different at $p < 0.05$.

3.1. Isolated eyes and head (Fig. 4)

Fig. 7 plots the judgments for images in Fig. 4, which include the straight and turned heads with eyes closed, and the isolated eyes both separately and together. The observers judged that the straight head with closed eyes (Sxx) was almost perfectly straight (−0.07°). However, the observers judged that the head with closed eyes, which was turned −30° to the observer's left (Txx), was only turned about half the true amount (−13.60° vs. −30°).

The observers judged that the paired straight eyes isolated from a straight head (aa) were close to straight (+0.12°). However, they judged that when the eyes were displayed individually, the eye to the left (ax) was biased −1.28° to the left ($p < 0.002$) while the eye to the right (xa) was biased +1.02° to the right ($p < 0.02$), which gave an angular separation of 2.30° between the two eyes.

For eyes gazing at +30° that were isolated from a straight head (bx, xb, and bb), all group mean judgments significantly underestimated the true direction of gaze. Observers underestimated the true direction of gaze for the eye to the left (bx) (+13.79°) more than gaze from the eye to the observer's right (xb) (+21.22°) ($p < 0.001$), whose judged direction of gaze did not differ significantly from the judgment based on both eyes together (bb) (+21.07°).

For eyes gazing at −30° that were isolated from a head that was turned −30° (cx, xc, and cc), all group means again significantly underestimated the true direction of gaze. Judgments on the eye to the left (cx) (−15.87°) underestimated the true direction of gaze less than the eye to the right (xc) (−10.26°) ($p < 0.01$) and did not differ significantly from the judgment based on both eyes together (cc) (−16.88°).

For eyes gazing at 0° that were isolated from a head turned −30° (dx, xd, and dd), all group means estimated that the direction of gaze was to the right of the true 0° direction of gaze. Gaze from the eye to the left (dx) (+3.70°) was judged to be closer to the true direction of gaze than gaze from the eye to the right (xd) (+6.35°) ($p < 0.002$), whose judged direction of gaze did not differ significantly from the judgment based on both eyes together (dd) (+7.25°).

3.2. Eyes congruent with the head (Fig. 5)

We combined the images in Fig. 4 to produce the images in Fig. 5, which show all combinations of 0° and −30° head turn and 0° and ±30° gaze as these combinations would naturally appear (eyes congruent with the head). Judged direction of gaze for the heads with congruent eyes is graphed in Fig. 8.

For eyes gazing at 0° on a straight head (Sax and Sxa) the eye to the observer's left (Sax) was judged to deviate slightly to the left (−0.70°) while the eye to the observer's right (Sxa) was judged to

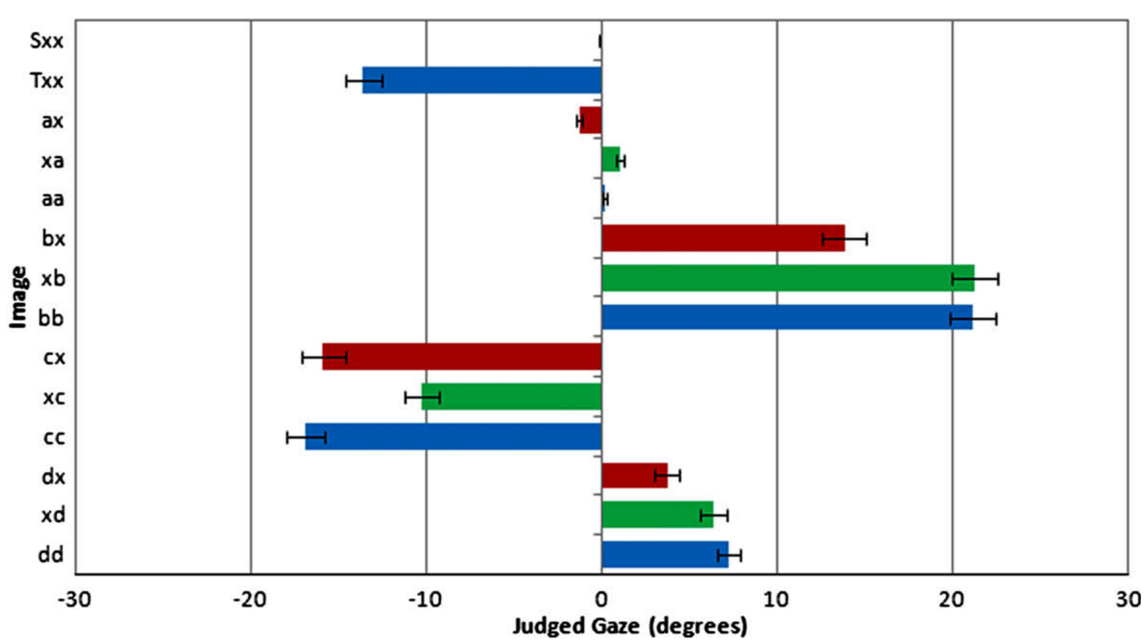

Fig. 7. Judged direction of gaze for the images in Fig. 4. 0° Represents gaze and head turn directed toward a point 50 cm from the model on a line between the model and camera #1. ±30° Represents gaze and head turn directed toward a point ±30° lateral to 0°. The whiskers represent ±1 standard error. Red bars represent gaze from the eye to the left, green bars represent gaze from the eye to the right, and blue bars represent binocular gaze. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

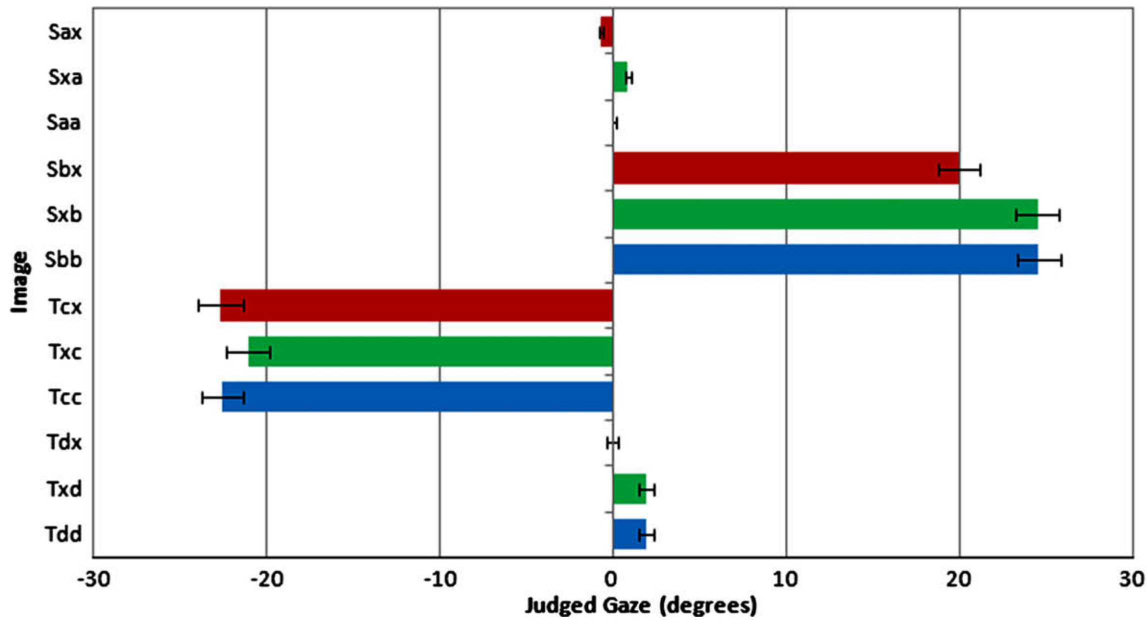

Fig. 8. Judged direction of gaze for the images in Fig. 5 in which the eyes were congruent with the heads. 0° represents gaze and head turn directed toward a point 50 cm from the model on a line between the model and camera #1. ±30° Represents gaze and head turn directed toward a point ±30° lateral to 0°. The whiskers represent ±1 standard error. Red bars represent gaze from the eye to the left, green bars represent gaze from the eye to the right, and blue bars represent binocular gaze. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deviate slightly to the right (+0.87°). With both eyes open (Saa) gaze was judged to be close to straight (+0.04°).

For eyes gazing at +30° from a straight head (Sbx, Sxb, and Sbb) the group means underestimated the true direction of gaze, just as for the isolated eyes. As before, observers underestimated gaze from the eye to the observer's left (Sbx) (+19.98°) more than gaze from the eye to the observer's right (Sxb) (+24.53°) ($p < 0.002$), whose judged direction of gaze did not differ significantly from the judged direction for both eyes open (Sbb) (+24.57°).

For eyes gazing at −30° from a head turned −30° (Tcx, Txc, and Tcc), the observers underestimated the true direction of gaze. Whether right, left, or both eyes were open made no significant difference (−22.71°, −21.07°, and −22.55°, respectively).

For eyes gazing at 0° from a head turned −30° (Tdx, Txd, and Tdd), the eye to the left (Tdx) was judged to be looking close to 0° (−0.03°). Judgments for the eye to the observer's right (Txd) and both eyes together (Tdd) were biased slightly to the right of 0° with no significant difference between them (+1.90° and

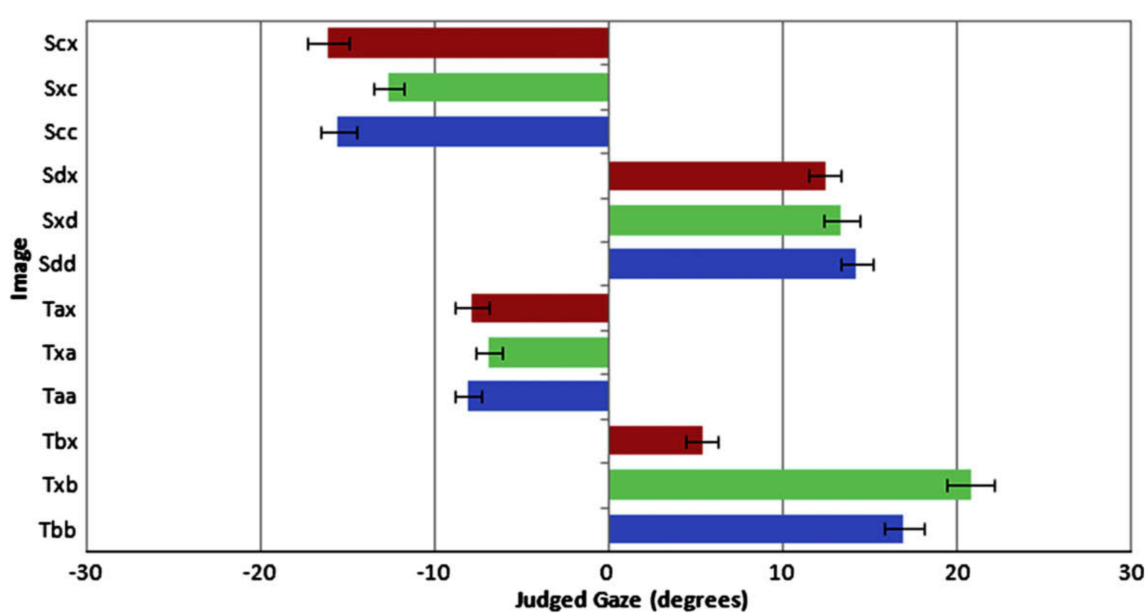

Fig. 9. Judged direction of gaze for the images in Fig. 6 in which the eyes were incongruent with the heads. 0° represents gaze and head turn directed toward a point 50 cm from the model on a line between the model and camera #1. ±30° Represents gaze and head turn directed toward a point ±30° lateral to 0°. The whiskers represent ±1 standard error. Red bars represent gaze from the eye to the left, green bars represent gaze from the eye to the right, and blue bars represent binocular gaze. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

+1.90°, respectively). Thus, for this condition, opposite head and eye turn almost completely canceled one another.

3.3. Eyes incongruent with the head (Fig. 6)

The images in Fig. 6 were constructed by swapping the eyes in the images in Fig. 5 horizontally across. Thus, Saa and Tcc become Scc and Taa, and Sbb and Tdd become Sdd and Tbb. Judged direction of gaze for the heads with incongruent eyes is graphed in Fig. 9.

For eyes gazing at −30° from a head turned −30° that were layered onto a straight head (Scx, Sxc, and Scc), gaze was judged to be in the direction of the head turn, but it was again significantly short of −30°. Although, the differences between pairings did not reach statistical significance, the trend was similar to that for when the same eyes were displayed isolated from the head (cx, xc and cc in Fig. 7).

For eyes gazing at 0° from a head turned −30° that were layered onto a straight head (Sdx, Sxd, and Sdd), gaze was judged to be to the right of 0° (+12.41°, +13.37°, and +14.23°, respectively). The only significant difference among the three was between Sdx and Sxd ($p < 0.05$).

For eyes gazing at 0° from a straight head that were layered onto a head turned −30° (Tax, Txa, and Taa), gaze was judged to be pulled from its true direction of 0° (−7.82°, −6.89°, and −8.10°, respectively) but there were no significant differences between the three.

Table 1
Mean judged gaze (in degrees) from straight ahead for right, left and both eyes within each image. A Friedman test (χ^2) determined which triplet sets contained unequal medians. For those triplets where $p < .05$ a sign test was run on each of the three possible pairings.

Image	Mean degrees	χ^2 ($df = 2$)	P	Sign test	p
Sxx	−0.07	N/A	N/A	Sxx/Txx	<.001
Txx	−13.60	N/A	N/A	–	–
ax	−1.28			ax/xa	<.01
xa	1.02	19.9	<0.001	ax/aa	<.002
aa	0.12			xa/aa	<.02
bx	13.79			bx/xb	<.001
xb	21.22	23.1	<.001	bx/bb	<.002
bb	21.07			xb/bb	–
cx	−15.87			cx/xc	<.01
xc	−10.26	15.6	<.001	cx/cc	–
cc	−16.88			xc/cc	<.01
dx	3.70			dx/xd	<.002
xd	6.35	8.3	<.02	dx/dd	–
dd	7.25			xd/dd	–
Sax	−0.70			Sax/Sxa	<.002
Sxa	0.87	22.6	<.001	Sax/Saa	<.002
Saa	0.04			Sxa/Saa	<.002
Sbx	19.98			Sbx/Sxb	<.002
Sxb	24.53	19.3	<.001	Sbx/Sbb	<.002
Sbb	24.57			Sxb/Sbb	–
Tcx	−22.71			Txc/Txc	–
Txc	−21.07	4.3	–	Tcx/Tcc	–
Tcc	−22.55			Txc/Tcc	–
Tdx	−0.03			Tdx/Txd	<.002
Txd	1.90	21.7	<.001	Tdx/Tdd	<.001
Tdd	1.90			Txd/Tdd	–
Scx	−16.10			Scx/Sxc	–
Sxc	−12.62	3.6	–	Scx/Scc	–
Scc	−15.54			Sxc/Scc	–
Sdx	12.41			Sdx/Sxd	<.05
Sxd	13.37	6.1	<.05	Sdx/Sdd	–
Sdd	14.23			Sxd/Sdd	–
Tax	−7.82			Tax/Txa	–
Txa	−6.89	6.1	<.05	Tax/Taa	–
Taa	−8.10			Txa/Taa	–
Tbx	5.37			Tbx/Txb	<.001
Txb	20.81	28.3	<.001	Tbx/Tbb	<.001
Tbb	16.93			Txb/Tbb	–

For eyes gazing at +30° isolated from a straight head that were layered onto a head turned −30° (Tbx, Txb, and Tbb), the direction of gaze was judged to be between the direction of the head turn and the true direction of gaze. Tbx was significantly smaller than Txb and Tbb ($p < 0.001$).

The pattern of results in Table 1 suggests that both the abducting eye and the head are important cues. To test this suggestion directly, a two-way non-parametric analysis was conducted (Bradley, 1968). The first factor was the straight head (present or absent), and the second factor was which turned eye was revealed (abducting or adducting). The measure was the degree of error. Thus, the analysis had four conditions: adducting eye alone (bx), abducting eye alone (xb), adducting eye with straight head (Sbx), and the adducting eye with straight head (Sxb).

The analysis suggests a main effect for the eye factor. Whether the head was present or not, when the abducting eye was revealed (xb and Sxb) 17 of 20 participants were more accurate as compared to when the adducting eye was revealed (bx and Sbx), sign test $p < 0.05$. The mean error for the abducting eye was 10.01°, as compared to an error of 13.48° for the adducting eye. There was also a main effect for the head factor. Whether the adducting or abducting eye was revealed, when the straight head was present (Sxb and Sbx) 15 of 20 participants were more accurate as compared to when the straight head was absent (xb and bx), sign test $p < 0.05$.

There was also an interaction effect. When the straight head was added, the improvement in accuracy was greater in 16 of 20 participants for the adducting eye (a mean improvement of 5.47° from bx to Sbx) than it was for the abducting eye (a mean improvement of 1.88° from xb to Sxb), sign test $p < 0.05$.

Additional insight into gaze detection is obtained by a two-way analysis of the photos in Fig. 5. With a straight head, an eye turn from forward to 30° (from Saa to Sbb) was judged to be a change of 24.53°; with a turned head, an eye turn from forward to 30° (from Tdd to Tcc) was judged to be a change of 20.65°. Both are underestimates, but the underestimation is greater when the head was turned (Wilcoxon signed-rank test, $z = 2.54$, $p = 0.01$). The difference in underestimation found in two eyes is not present with the left eye. With a straight head, an eye turn from forward to 30° (from Sbx to Sax) was judged to be a change of 20.68°; with a turned head, an eye turn from forward to 30° was judged to be a change of 22.74°. The two underestimates do not differ significantly from one another (Wilcoxon signed-rank test, $z = 1.57$, $p = 0.12$). However, it is found for the right eye. When the head was straight, a shift of 30° by the right eye (from Sxa to Sxb) was judged as a mean shift of 23.65°; when the head was turned, a shift of 30° by the right eye (from Txd to Txc) was judged as a mean shift of 19.18°. Both were underestimates, but the underestimate was greater when the head was turned (Wilcoxon signed-rank test, $z = 3.62$, $p < 0.001$).

This underestimation increased when the head was removed, leaving only the isolated eyes in Fig. 4. A 30° turn by eyes isolated from a straight head (aa to bb) was perceived as a change of 20.95°; however, a 30° turn by eyes isolated from a turned head was perceived as a change of 9.63°. Both were underestimates, but the underestimate was greater in the eyes isolated from a turned head (Wilcoxon signed-rank test, $z = 3.88$, $p < 0.01$). These data suggest that observers had more difficulty in accurately judging gaze when the head was turned, and this difficulty was increased when the head was absent as a cue.

4. Discussion

Previous studies have used images of heads with various degrees of detail, which have ranged from schematic line-drawn heads, to computer-generated heads, to photographs of heads, to live heads. Each style has been effectively used to study different cues to gaze, either in isolation or in combination with other facial cues. For instance, Maruyama and Endo (1983) and Todorovic (2009) used line-drawn heads in order to study the effect of eccentricity of the eyes and nose on the perceived direction of gaze, and Todorovic (2006) used computer-generated heads to study the relationship between iris and head eccentricity. Although, schematic and computer-generated heads allow an easier interpretation of the function of isolated facial cues, photographic images allow us to determine the effect that the normally observed constellation of cues has on natural gaze. For instance, simplified images usually depict the eyes in straight gaze to be toward a distant object with the irises centered within the lid apertures, and in averted gaze with the irises symmetrically displaced with respect to the two lid apertures. On the other hand, the irises of real eyes are usually decentered temporally in straight gaze (due to angle κ), and they move toward nasal decentration when they gaze toward closer objects. Also, when a head is turned and the eyes counter-rotate to maintain eye contact on a near object, the eye toward the direction of the head turn (the adducting eye) will turn more than the eye away from the direction of the head turn (the abducting eye). Images that depict only symmetrical iris eccentricities miss this aspect of gaze.

In order to make our results as applicable to true gaze as possible, we used images that: were in color; were life-size; had known angle kappas; and were viewed at the same distance at which the images were captured. In addition, we have analyzed our results for each eye individually, as well as for both eyes together. As our results demonstrate, the two eyes did not individually appear to be gazing at the same point, even when natural convergence was depicted and their directions of gaze were corrected for angle kappa.

4.1. Isolated single vs. isolated paired eyes

When our observers viewed the paired straight eyes that were isolated from the straight head (aa) they judged their direction of gaze accurately (+0.12° = 7.2 min), although less accurately than the thresholds reported by Gibson and Pick (1963) and Cline (1967), which were 1.01 min and 0.51 min, respectively. However, when they viewed the eyes individually (ax, xa) they judged their gaze to be deviated outward from one another by a total of 2.30° ($p < 0.01$, Table 1). Symons, Lee, Cedrone, and Nishimura (2004), using a live model, found a similar result. When both of their model's eyes were visible the error was less than 0.1° (estimated from their Fig. 2B). But, when they covered the eye to the right so that only the eye to the left was visible, the error increased to about 2.5° to the left. We believe that this difference in error between the individual and paired eyes in our data and that of Symons, et al. was because the left eye had a typical positive (outwardly deviated) angle kappa. They would probably have found the same effect if they had also tested the right eye alone.

Because the outlines of real heads have imperfect mirror symmetry it is difficult on that basis to specify when a head is straight. Instead, as our model gazed at the camera lens we turned her head to the orientation for which her two eyes appeared to have mirror symmetry with respect to the location of the irises within her lid apertures. The value of angle kappa for an eye is invariant with head turn, so that even when the eyes counter-rotate with head turn, the difference between the angle kappas of the two eyes remains constant. This explains why the 2.29° angular separation between the two pupillary axes (the sum of the two angle kappas) was in good agreement with the perceived 2.30° gaze separation between the isolated eyes (ax and xa in Table 1). Although, the two eyes had dissimilar angle kappas (+0.46° for the eye to the left and +1.83° for the eye to the right) in contrast to the similarity of their judged gaze (−1.28° for the eye to the left and +1.02° for the eye to the right), this difference was due to an approximately 0.8° head turn to the right of the position where the eyes would have been oriented along their respective angle kappas. If the head had been turned slightly less to the observer's right the judged angles of gaze for the two eyes might have been even more equal. We were able to get this close because we took multiple sets of images of our model as we reoriented her head about the direction that we considered to be straight, and then used Photoshop to select the set for which the irises were most symmetrical within her lids.

When the eyes were shown as pairs that were isolated from the head (or against the head as will be described in Section 4.2.1), the separation in the judged direction of gaze between the two eyes became much smaller, which we believe was because the observers subconsciously averaged the opposing directions of the angle kappas for the two eyes. According to this explanation Cline (1967) and Gibson and Pick (1963) found such low errors because they presented their eyes as pairs. This increased level of accuracy in binocular gaze is consistent with the theories that claim that observers compare the symmetry between the two eyes (Ando, 2002; Anstis et al., 1969; Symons et al., 2004; West & VanVeen, 2007; Wollaston, 1824).

Although, the angle kappas for the eyes of an individual tend to be symmetrical, they are not always so, and any asymmetry would decrease the accuracy of the judged direction of gaze. Since normal angle kappas average 5° by one report (Emsley, 1963), are variable, and are not detectable by casual observation, they can influence where individual eyes appear to be looking in an apparently random way. This demonstrates the importance of measuring the angle kappas when using photographed and live models.

4.2. The combined effect of the perceived directions of head and eye turn

Todorovic (2006) introduced the use of vector diagrams to evaluate the head turn effect and suggested that perceived gaze direction can be treated, to a first approximation, as a simple geometrical problem that uses the addition of vector angles to calculate gaze direction as a function of eye and head turn. He proposed the equation $\gamma = \kappa + \lambda$, where γ is the observer-related gaze direction, κ is the observer-related head direction, and λ is the looker-related gaze direction. Because differences in angle kappa would change the correspondence between iris eccentricity and perceived direction of gaze, κ may be included as an additional term in this equation. However, since the symbol κ is already used in visual optics to note the angle between the line of sight and the pupillary axis (and even λ is sometimes used as an alternate symbol for κ), we suggest changing the symbols so that the equation reads $\gamma = \alpha + \beta$, so that κ can be used with its traditional meaning.

Because the images of our model were confined to head turns that were 0° or −30°, and eye turns that were −30°, 0°, or +30°, this equation can easily be used to analyze the relative effect that head and eye turn have on the perceived direction of gaze. For example, if a head turn of $\alpha = -30°$ (Txx in Fig. 4) and an eye turn relative to the turned head of $\beta = +30°$ (dd in Fig. 4) were judged accurately, then $\gamma = -30° + 30° = 0°$ and the gaze would be perceived as giving eye contact.

Given that the perceived directions of head and eye turn were not accurate it is still possible that the vector equation would predict the perceived direction of gaze if the *perceived* directions of gaze were entered into it. Thus, the perceived direction of head turn would serve as a background against which the perceived direction of gaze relative to the head turn would be added. In the above example, the −30° head turn (Txx) was perceived to be −13.60°, and the +30° eye turn (dd) relative to the turned head was perceived to be +30° + 7.25° = +37.25°. Then, if the values for the perceived directions were additive, the predicted perceived direction of gaze would be $\gamma = -13.60° + 37.25° = +23.65°$. However, the actual perception of gaze from the head that combined these two features (Tdd in Fig. 5) was +1.90°. This demonstrates that the perceived orientation of an isolated head and the perceived direction of gaze from isolated eyes are not additive. This lack of prediction is probably because the images of the isolated eyes (dd) did not retain sufficient background cues to maintain the impression that they were located on a plane that was tilted −30°, so the observers perceived them to be on a relatively flat plane, which made them appear to be looking far to their right.

As another example, if a head turn of $\alpha = -30°$ relative to the observer (Txx in Fig. 4) and an eye turn of $\beta = 0°$ relative to the head orientation (cc in Fig. 4) were judged accurately, and the values for the perceived directions were additive, then $\gamma = -30° + 0° = -30°$ and the gaze would be perceived to be directed −30° to the observer's left. However, the head turn was perceived to be −13.60°, and the eye turn was perceived to be $\beta = -13.60° - (-16.88°) = -3.28°$ to the left of the perceived head orientation. The predicted gaze direction relative to the observer would then be, $\gamma = -13.60° - 3.28° = -16.88°$. The actual perception of gaze from Tcc (Fig. 5), which combined these two features, was −22.55°. This lack of prediction must be almost entirely due to the perceived amount of head turn since the eyes were judged to deviate from the perceived head turn by only 3.28°. This observation is in agreement with Langton et al. (2004) who reported that judgment of gaze was best when the eyes gazed in the same direction in which the head was oriented.

The above examples were for binocular gaze. If κ were included, separate versions of the equation would be required for monocular and binocular gaze. For monocular gaze the equation would be $\gamma = \alpha + \beta \pm \kappa$, where κ is for the open eye, and since κ is plus when the pupillary axis is temporal to the line of sight, in the equation κ is plus for the abducting eye and minus for the adducting eye. However, when averted binocular gaze was shown using isolated eyes (bb and dd) or eyes layered against a straight or turned head (Sbb and Tdd,), the perceived direction of binocular gaze always followed the perceived direction of gaze from the abducting eye (xb, xd, Txb, and Txd). Therefore, for binocular gaze the equation would be $\gamma = \alpha + \beta \pm \{f(\kappa_1) - \kappa_2\}$, where κ_1 is for the adducting eye, κ_2 is for the abducting eye, and $f(\kappa_1)$ represents a function of κ_1 that is dependant on α and β. An explicit expression for $f(\kappa_1)$ cannot be determined from our data, but it can be seen that it would decrease with increasing gaze angle. For small gaze angles (α and β), $f(\kappa_1) = \kappa_1$, so that for the typical symmetrical angle kappas $f(\kappa_1) - \kappa_2 = 0$. For larger gaze angles $f(\kappa_2)$ would decrease as the judgment of binocular gaze transitions from following the mean of the angle kappas to following the abducting eye. In the above examples, which analyzed binocular gaze involving large angles, $f(\kappa_1)$ was assumed to be 0° and $\kappa_2 = 1.02°$. Kappa is generally small enough so that it is only important when α and β are small. Thus, κ is important when the head and gaze are close to straight, and especially so when gaze is monocular. Although, monocular gaze is seldom seen in a natural setting, it is important when studying it as a component of binocular gaze. For example, any asymmetry in κ between the two eyes would influence the threshold for binocular gaze.

4.2.1. Straight head with congruent eyes

Our data show that when the *single* eyes that were directed toward 0° (ax and xa) were layered onto the straight head (Sax and Sxa) they were judged to be deviated outward from each other by a difference of 1.58° ($p < 0.002$, Table 1). This was slightly smaller than the summed outward deviation of gaze that was perceived when the isolated eyes were viewed individually, but the difference between isolated and layered eyes was not statistically significant.

When *paired* eyes that were directed toward 0° were layered onto the straight head (Saa), the addition of the head also added little to the accuracy of judged gaze from the paired eyes alone. Judgment of straight gaze from the paired eyes that were layered onto the straight head (Saa in Fig. 8) (+0.04°) was slightly more accurate than straight gaze from the paired eyes that were isolated from the head (aa in Fig. 7) (+0.12°). In both cases gaze was judged to be close to straight. This would be expected since there was little room for improvement between judgments from isolated pairs of eyes and pairs of eyes layered onto the head.

4.2.2. Turned head with congruent eyes

We isolated the eyes without the head and the head both with and without the eyes so that we could determine how each of those cues in isolation and in combination would influence the judged direction of gaze. The observers viewed the isolated single eyes first, then the isolated paired eyes, and finally the head with and without eyes. We displayed the isolated eyes first in order to minimize knowledge of the orientation of the facial plane when their direction of gaze was judged. Without the background head the cues to the true plane of the face would be reduced, which would be especially important for a head that is at a large angle. For instance, although examples of isolated single eyes are not shown in Fig. 6, casual inspection of images cc and dd shows that the cues to the true plane of the head are reduced by covering one of the eyes in each pair. For the above reasons, we cropped more of the surrounding face from the eyes than Langton et al. (2004) did. An inspection of their isolated paired eyes which they obtained from a turned head shows that they convey a considerable amount of information about the facial plane.

Even if lid structure and angle kappa were symmetrical and the eyes were straight, a perceived asymmetry would be induced if the eyes and/or head were turned. As pointed out by Langton et al. (2000) the irises of straight eyes are typically closer to the nasal than the temporal border of the lid aperture, so in straight gaze from a straight head more temporal than nasal sclera is exposed. However, an asymmetry would be produced by eyes that are turned relative to a straight head (see bb in Fig. 4) or straight relative to a turned head (see cc in Fig. 4). Also, since the face is curved, the lid aperture on the side toward which a head is turned wraps around the facial curve and is foreshortened, which results in a further asymmetry (also pointed out by Langton et al. (2000)). Both of these eye and head-turn-induced asymmetries can also be produced in the same image (see dd in Fig. 4).

Wilson et al. (2000) studied which facial cues established the perception that a head is turned and suggest that there are two important equal strength cues; the deviation of the head contour from bilateral symmetry, and the deviation of the line from the bridge to the tip of the nose from vertical. However, they speculated that the head contour may become less important than the nose angle when the head turn approaches 30°.

Whereas Wilson et al. (2000) studied which head features were used to determine the degree of head turn, Langton et al. (2004) confirmed that those same features were used to determine the direction of gaze. Langston et al. tested the ability of observers to detect whether gaze from straight and turned heads was direct or averted when the eyes were deviated ±16° from looking directly at the observer. Observers were able to distinguish direct from averted gaze best when the head and eyes were turned in the same direction, next best when the paired eyes were shown isolated from the head outline, and least well when the head and eyes were turned in opposite directions. Because the gaze effect was eliminated by the inversion of the head for the nose but not for the head contour, they reasoned that head contour exerted its effect via a low-level process while the nose angle used a later stage of processing. Jenkins and Langton (2003) also found that the threshold for gaze direction was higher when the eyes were viewed in isolation from the head.

In our study, although the addition of the head made little difference in the judged accuracy when the eyes were straight, it improved accuracy when the eyes were turned +30° relative to the straight head (Figs. 5 and 8). For both layered and isolated eyes, judgments were more accurate for the abducting eye (Sxb and xb) as compared to the adducting eye (Sbx and bx). The addition of the head improved accuracy as well; however, there was an interaction effect so that the improved accuracy was greater for the adducting eye. The opposing positive angle kappas could account for some of the judged difference between adducted and abducted eyes but would not be large enough to account for all of it.

We conclude that judged direction of gaze from isolated eyes is improved by adding a head as background, and that, with binocular gaze, the net direction of gaze is determined by the abducting eye. This suggests that research restricted to heads which only give binocular gaze may be missing an interesting part of the analysis.

An analysis of the judged direction of gaze from a turned head must include the likelihood that the direction in which the head is judged to be pointed may itself show a bias. In fact, Fig. 7 shows that the turned head with closed eyes (Txx) was judged to be turned less than half of its true amount (−13.60° vs. −30°). The background of a turned head might then be expected to bias by the same amount the perceived direction of gaze from eyes that are straight relative to the turned head (Tcc). However, the *isolated* eyes that were straight relative to the turned head were also judged to be turned less than the true amount. Therefore, the isolated eyes had an underestimation bias that was independent of the head. The observers judged cx and cc to be turned about half of the true amount (−15.87° and −16.88° vs. −30°) and xc to be turned about one-third of the true amount (−10.26° vs. −30°). This difference between the judged direction of gaze between the right and left eyes is probably because the eye to the left (cx) revealed less temporal sclera which, in the absence of a background turned head, would be interpreted as being turned more temporal than the eye to the right (xc). Nevertheless, when these eyes were layered against the turned head, the judged direction of gaze was dramatically improved and the amount of turn for both single and paired eyes was about equal.

One might expect that gaze toward 0° from a head turned to the observer's left would be judged as gazing at 0°. However, our model's binocular gaze (Tdd) was judged to be +1.90° to the observer's right. This replicates the head turn effect first reported by Gibson and Pick (1963). When the eyes were viewed individually against the turned head, the eye to the left (Tdx) was judged to have almost no bias (−0.03°) while the eye to the right (Txd) was judged to have the same bias as when both eyes were viewed (Tdd) (both were +1.90°). When the eyes were isolated from the head their judged biases increased but the eye to the left (dx) still had the smallest bias (+3.70°), and the eye to the right (xd) still closely matched the bias of both eyes viewed together (dd) (+6.35° vs. +7.25°, respectively). Thus, for the turned eyes isolated from the turned head, the judged direction of the abducting eye still followed that of both eyes together, but in this case judged binocular gaze was less accurate.

This difference in bias between the right and left eyes can, at least in part, be accounted for by the model's angle kappas. A left deviating pupillary axis for the eye to the left of the observer would counteract the head turn effect for that eye while a right deviating pupillary axis for the eye to the right would add to it. This again demonstrates the importance of measuring angle kappa since it varies between individuals.

The previously mentioned study by Noll (1976) sheds light on this problem. Noll reported that when a model's head was turned and one or the other eye masked, the farther (adducting) eye seemed to look at the observer while the nearer (abducting) eye seemed to be looking away from the observer in a direction opposite to the head turn. When only the nearer (abducting) eye was visible, the errors matched those for when both eyes were visible. Noll concluded that the error when both eyes were seen occurred because the observer gave greater weight to the nearer (abducting) eye. This would lead to the conclusion that binocular gaze is driven by the less accurate eye! While our results agree our interpretation differs. Although, the adducting eye seemed to more accurately look at the observer than the abducting eye, this may be due to a typical positive angle kappa for each eye, which would result in a perceived temporal deviation for each eye. Thus, for a zero angle kappa, the abducting eye would be the more accurate, along with the perception of eye contact from binocular gaze. This same effect was reported by West and VanVeen (2007) in which, for both the original painted eyes and the photographed eyes that were layered onto Vermeer's *Girl with a Pearl Earring*, the abducting eye followed the judged binocular gaze, while the adducting eye was closer to giving perceived eye contact.

It is easy to confirm, even in casual social encounters, that when a head that is facing you shows averted gaze, the adducting eye reveals more sclera to the side opposite the gaze than the abducting eye does, and as gaze becomes more eccentric it usually loses scleral exposure first. This is, no doubt, due to the greater exposure of temporal than nasal sclera in straight gaze and the fact that for near targets the adducting eye must turn farther than the abducting eye. This also occurs when a turned head gives you eye contact, and in extreme cases the bridge of the nose may occlude the nasal side of the adducting eye. This is a possible reason why, given conflicting perceived directions of gaze from the two eyes, the abducting eye is used to assess the direction of binocular gaze.

We conclude that with binocular gaze from both straight and turned heads, the net direction of gaze is determined by the abducting eye. We suggest that Txd and Tdd gave an overestimate relative to 0° whereas Tdx was virtually on top of it, because Txd exposed the abducting eye.

4.2.3. The Wollaston effect

The Wollaston effect is the perception that, when eyes are isolated from their natural head and layered against a head that is turned in a different direction, their direction of gaze is drawn towards the orientation of the new head. The resultant chimera would, of course, never be seen that way in real life and would appear abnormal. Nevertheless, the Wollaston effect is another way to look at the interaction between eye and head turn, so it is useful as a tool to study the more general gaze effect. It is, of course, also of interest to study the images in their own right because Wollaston figures are well-known and entertaining illustrations.

A Wollaston image may look unnatural when eyes from a turned head are layered onto a straight head (Scc and Sdd in Fig. 6) and anatomically impossible when eyes from a straight head are layered onto a turned head (Taa and Tbb in Fig. 6) in part because, with a turned head, the distance between the eyes and the width of the eyes is foreshortened, mostly on the side toward the head turn. We could have reduced the distance between the two eyes and the widths of the eyes in order to make them look more natural. However, we kept the eyes unchanged so that we could compare gaze from the layered eyes with the *identical* eyes in isolation, and also to analyze the Wollaston effect as it is usually illustrated, which includes eye-head configurations that look anatomically odd.

If we layer bb (the eyes that were isolated from a straight head) onto Txx (Fig. 4) we obtain the most popular Wollaston image, Tbb

(Fig. 6). The −30° head turn of Txx was perceived to be −13.60°, and the +30° eye turn of bb relative to a straight head was perceived to be +21.07°. Then, the predicted gaze $\gamma = -13.60° + 21.07° = +7.47°$. However, observers judged the direction of gaze of the Wollaston image Tbb to be +16.93°.

Tdd, the normal head that corresponds to Tbb, superficially looks similar to Tbb but was judged to gaze +1.90° to the right as opposed to +16.93° to the right for Tbb. This difference between the judged directions of gaze was probably caused by the perception that the plane of the turned eyes (bb) appeared to be tilted toward the perceived angle of the plane against which they were layered. When monocular gaze was displayed, Tbx was judged to gaze +5.37° to the right, whereas Txb was judged to gaze +20.81° to the right. Therefore, the eye to the right seems to have had a greater influence on establishing the +16.93° judged direction of gaze from Tbb than the eye to the left did. This seems counterintuitive since the eye to the right has an appearance that is very similar to the corresponding eye in Tdd, while the eye to the left exposed more sclera temporal to the iris compared to the eye to the left in Tdd. The extra temporal sclera in the eye to the left should be a cue that makes the plane of that eye more resistant to being perceived as turned in the direction of the background head, which should make the eye appear to gaze farther to the right. This would also be predicted by the iris location theory. The eye to the left, when isolated (bx), was judged to gaze at +13.79° while the eye to the right (xb) was judged to gaze at 21.22°, so the difference in gaze between the two eyes was partially present even when the two eyes were isolated from the head. Apparently the rule that the abducting eye establishes the perceived direction of binocular gaze has a powerful influence on the perceived direction of gaze even when the image is a very non-anatomical Wollaston head.

If we layer aa (the straight eyes isolated from a straight head) onto Txx (Fig. 4) we obtain the Wollaston image Taa (Fig. 6). The −30° head turn of Txx was perceived to be −13.60°, and the 0° eye turn of aa relative to the straight head was perceived to be +0.12°. Then, the predicted perceived direction of gaze would be $\gamma = -13.60° + 0.12° = -13.48°$. This disagrees with the true judged direction, which was −8.10° to the left of the observers.

The natural image that corresponds to Taa is Tcc (Fig. 5), which had a judged direction of gaze of −22.55°. The difference between the perceived direction of gaze for Tcc (−22.55°) and Taa (−8.10°) is probably because the isolated eyes in aa were less influenced by the turned head against which they were layered, possibly due to the lack of foreshortening of the eye in the direction of the head turn. The eye to the right in Taa looks very similar to the eye to the right in Tcc except that the iris is displaced more temporally. On the other hand, the eye to the left in Taa looks very different than the corresponding eye in Tcc, not only because the iris is displaced more nasal but because it wraps around the head so that less temporal sclera is visible than in Taa. This would lead to the expectation than the left eye in Tcc would appear to be pointed more temporal than in Taa. Since the two eyes in Tcc do not differ significantly in their direction of gaze the observers must have compensated for this asymmetry in the natural head. However, there was no significant difference in the judged direction of gaze for either eye in Taa. Therefore, we conclude that the head turn does not disrupt the symmetry present in straight gaze. When monocular gaze was judged for Taa, the eye to the left (Tax) was judged to gaze −7.82° to the left of the observer whereas the eye to the right (Txa) was judged to gaze −6.89° to the left of the observer. Thus, the gaze from the eyes which were isolated from the straight head was very similar, but, when layered onto the turned head it was very different. The plane of the turned head, in this case, was responsible for the difference in gaze between the natural head (Tcc) and the Wollason head (Taa).

The gaze again follows the rule that binocular gaze is judged by the abducting eye (Txb). This is easily seen by casual inspection of the eyes to the observer's right in Sbb and Tbb which look very similar. This, in fact, may be the reason that given two eyes on the same head whose directions of gaze appear to differ, the abducting eye is selected. It is less foreshortened with a head turn and easier to interpret.

Another variation of the Wollaston figures (Scc in Fig. 6) is created when eyes that are straight relative to a turned head (Tcc in Fig. 5) are layered onto a straight head (Sxx in Fig. 4) to produce Scc (Fig. 6). Would they show a similar effect in which the eyes are turned toward the direction of the head, in this case straight? Tcc, Tca, and Txc, as we have seen, underestimate the true direction of gaze (Fig. 8). However, Scc, Scx, and Sxc underestimate the true direction even more, showing that the judged direction of gaze is pulled toward the direction of the head, which is straight in this case. Therefore, this configuration also results in a sizeable Wollaston effect.

A final variation of the Wollaston figures (Sdd in Fig. 6) is created when turned eyes from a turned head (Tdd in Fig. 5) are layered onto a straight head (Sxx in Fig. 4) to produce Sdd (Fig. 6). The judged directions of gaze for Tdd, Tdx, and Txd were all close to 0°. However, when the eyes were layered onto a straight head, the eyes appeared to gaze appreciably to the observer's right, but much less so than natural eyes gazing from a straight head (Sbb). Thus, the straight head pulled the perceived direction of gaze toward 0°.

4.3. The role of target distance

Those studies that have placed the fixation targets about half way between model and observer (Anstis et al., 1969; Imai, Sekiguchi, Inami, Kawakami, & Tachi, 2006) have reported that the judged direction of gaze was overestimated compared to the true direction. On the other hand, studies that have placed the target in the plane of the observer's face (Ellgring, 1970; Masame, 1990; West et al., 2008) have reported an underestimation. This led West et al. (2008) to agree with Masame that gaze toward the plane of the observer's face may result in underestimation whereas gaze toward a plane that is distant from the observer's face may result in overestimation. However, in the present study, for both straight and turned heads with either congruent or incongruent eyes, we have found an underestimation, so this apparently is not a firm rule. Procedural differences may account for this inconsistency, such as the psychophysical task, the size of the images, monitor resolution, the use of 2-D vs. 3-D models, control of angle kappa, or the distance between the model and the observers, among other possibilities.

For instance, if a short line were directed from a point in front of an observer at an angle to the observer, and the observer were to imagine its extension through a series of fronto-parallel planes, it is likely that a line connecting those intersections would be neither accurate nor straight. Thus, even if the configuration of the iris within the lids were identical, observers would judge gaze onto planes at different distances to be at different angular locations. Therefore, part of the perceived error between true and judged directions of gaze would be due to a perceptual distortion of the space between the gazer and the observer. Then, any complete model of how a given eye configuration would lead to a particular perceived direction of gaze would have to include a quantitative knowledge of that distortion. This paper has dealt only with the relationship between ocular cues and the judged direction of gaze, and in that sense our data are relative.

4.4. The limitations of 2-D heads

The assumption that data from 2-D imaged models would be similar to data from 3-D live models may not be justified since the addition of depth to a 2-D image would offer additional cues to the true direction of head and eye turn. For example, if a live 3-D model looks at a camera located directly in front of her and you move to the side of the camera, you will still perceive that she is looking at the camera. However, if you replace the model with a 2-D photograph taken by the camera and move to the side of the photograph, you perceive that her gaze moves away from the camera in your direction (the Mona Lisa effect).

If the heads are straight, judgment of gaze from 2-D and 3-D heads should be similar because the 3-D relief would be small and therefore offer little advantage over a 2-D image. And, in fact, judgment of direct gaze from a straight head has been found to be about as accurate with a 2-D image as with a live 3-D model (Symons et al., 2004). However, with a turned head a 3-D view may make a large difference in perceived gaze.

There are a number of studies that have studied gaze from live 3-D models with turned heads, either exclusively (Cline, 1967; Gibson & Pick, 1963; Masame, 1990) or in addition to imaged 2-D heads (Anstis et al., 1969; Gale & Monk, 2000; Gamer & Hecht, 2007; Imai et al., 2006;Yoshida, Kamachi, Hill, & Verstraten, 2005). Of particular interest is the study by Anstis et al. since they did not find a head turn effect when a live 3-D model gave direct gaze, but did find a head turn effect with a 2-D TV-imaged model. However, for both 2-D and 3-D heads judged gaze became less accurate with increasing angle of gaze, and gaze toward the direction of the head turn closely followed that for when the head was straight. In contrast, Masame (1990) designed a study to check the results of Anstis et al. and did find a head turn effect with a live 3-D model. Yoshida et al. (2005) also found a difference between 2-D and 3-D models in that the shift in perceived direction of gaze was smaller for 3-D than for the 2-D heads, although both still increased with greater head rotation and gaze angle. From the above, we suggest that if the heads are straight the extrapolation of results from 2-D heads to 3-D heads is probably justified, but if the heads are turned, such an extrapolation should be used with caution.

4.5. Theories of gaze

There are two main theories about what cues are used to determine the direction of gaze; one theory claims that iris pointing is the relevant cue while the other theory claims that iris location within the lid aperture is the relevant cue. (See for instance: Anstis et al., 1969; Langton et al., 2004; Symons et al., 2004.)

(1) The iris pointing theory proposes that observers mentally construct a line perpendicular to the center of the iris, which they perceive to be the direction of gaze. (2) The iris location theory proposes that observers note the location of the iris within the lid aperture such as: the distance of the iris from either the inner or outer corner of the lid opening; the ratio of the distances between the two corners; or the difference in the areas of the exposed sclera to each side of the iris, and then use this information to determine the perceived direction of gaze.

Both of these theories require that the observers must be able to detect very small changes in the rotation of the eyeball that correspond to differences in iris location at the limit of their visual acuity (1.0′ for 20/20). For example, Cline (1967) reported a standard deviation of 0.51 min and Gibson and Pick (1963) reported a value of 1.10 min. Cline also reported that the threshold was larger for larger angles.

There is evidence for and against each of these theories. When observers judge gaze from heads that have both their orientation and gaze turned away from them the situation becomes more complex than when head and eyes are straight. This presents a challenge to the iris location theory because the observer would have to have an algorithm to determine a direction of gaze for every combination of iris eccentricity and head orientation. However, a variation of the iris location theory avoids this problem. It proposes that the relevant cue to the direction of gaze is the luminance ratio between the exposed scleras on the two sides of the iris. Since this cue is non-spatial it would presumably be less limited by visual acuity than the other cues mentioned above. In support of this cue Watt (1999) reported that, when he increased the observer viewing distance, threshold for gaze detection did not drop off as fast as expected if ocular details were used, but the drop off was consistent with a comparison of the luminance. Also, Ando and Osaka (1998) found that darkening of the sclera on one side of the iris shifted the perceived direction of gaze toward that side, which, of course, does not change the spatial geometry of the iris between the lids. On the other hand, the iris location theory would predict that the adducting eye should show the greatest gaze eccentricity, but as our data show, it is the abducting eye that does.

The iris pointing theory avoids the complexity involved with all of the combinations of head orientation and iris location because it uses cues that come from the eyeball and the iris alone, which theoretically can operate independently from head turn. In support of the iris pointing theory, Anstis et al. (1969) have published evidence that gaze direction can be obtained from a model eyeball in isolation from head and eyelids. Observers viewed a ping pong ball which had a 6 mm pupil painted on it, which was set behind an adjustable diaphragm to simulate a lid aperture. When the diaphragm was enlarged so that it did not hide any part of the ping pong ball, not only could observers judge the direction of gaze, but many of the effects special to gaze were still present. Both the head turn effect and an overestimation effect still occurred.

Given the social importance of gaze discrimination, it is, of course, likely that all of the above cues play a variable and interactive role in the perception of gaze direction, depending on whether the head and/or gaze is direct or averted, the distance at which the eyes are observed, and the ocular detail available to the observer. We suggest that the cue to the direction of gaze is primarily iris location when gaze is close to being straight, but it then transitions to iris pointing as gaze becomes more averted.

5. Conclusion

Our study supports and extends many of the conclusions reported in the gaze literature. However, we have also discovered some features of gaze perception that have not been previously recognized. Particularly interesting findings are that, due to typical angle kappas, straight binocular gaze is judged more accurately than straight monocular gaze, and the judged direction of averted binocular gaze is determined more by the abducting eye, whether the head is straight or turned. Also, we have measured the direction of gaze from normal images and from a traditional Wollaston image and its variations, and have measured the effect for each eye exposed individually as well as together.

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