Peripheral Processing of Gaze

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Abstract

When looking at someone, we combine information about their head orientation and eye deviation to judge their direction of gaze. What remains unknown, however, is how these cues combine when we are not looking directly at the person, but rather using our *peripheral vision*. Given that peripheral vision helps direct future attention, understanding how we perceive other people's gaze is key to determining their future actions. To examine this we asked participants to categorise gaze direction in faces whose heads were turned in different directions, and which were viewed using either central or peripheral vision. We report that the weight given to head orientation increases in the periphery where forward facing heads were categorised as "direct" over a wider range of eye deviations than when viewed centrally. When peripheral heads were turned, the number of "direct" responses fell for all gaze deviations with no consistent shift in left/right responses towards the head rotation. For centrally presented heads, head-orientation typically repulsed the perceived direction of gaze, and our finding of no consistent shift in responses indicates that such effects are reduced in the periphery. This is not simply the result of poorer spatial resolution in the periphery, other influences, such as crowding and priors for gaze or head direction may play a role.

Introduction

Understanding where another person's gaze is directed is a crucial component of social interaction. Gaze direction can convey information about others' intentions, but can also disambiguate communication, and alter our interpretation of another's emotion (Adams Jr. & Kleck, 2005). Most previous research has examined gaze processing using forward (direct) facing heads presented in the observer's central visual field. However, in many real world situations, for example when interacting within a group, we must judge gaze-direction using only peripheral vision. Indeed, inasmuch as the main function of human peripheral vision is to direct eye movements towards salient stimuli, and that a face looking at us is highly salient, we might expect gaze-direction processing to operate effectively when stimuli are viewed with peripheral vision.

Single cell recording from the superior temporal sulcus of macaque monkeys (STS), indicate that there are specific pools of neurons sensitive to direct, leftwards averted and rightwards averted gaze deviations and head rotations (Perrett et al., 1985). Complimentary functional magnetic resonance imaging (fMRI) studies (Calder et al., 2007) have uncovered comparable regions in the human STS instantiating mechanisms selective for direction of gaze. Pools of neurons that activated in response to presentation of direct or averted gaze were adapted (i.e. their activity was reduced after prolonged exposure) and were associated with a corresponding shift in behavioural responses. Specifically, the perceived direction of gaze shifted away from the adapted direction (i.e. after leftwards adaptation, leftwards gaze directions appeared more direct). Building on these results, it has been suggested that humans process gaze using a multi-channel system, with at least three separate channels coding direct, leftwards and rightwards gaze deviations (Calder, Jenkins, Cassel, & Clifford, 2008).

Signalling of direct gaze is particularly important, informing us when another person's attention is directed towards us. Gamer and Hecht (2007) report that there is a fairly broad range of gaze directions that an individual perceives as being directed at them; a range referred to as the "cone of direct gaze" (CoDG). Using a categorisation technique, Ewbank et al (2009) showed this CoDG to be broad (8-9°) and, under conditions of uncertainty, humans have a prior expectation that gaze is directed towards them (Mareschal, Calder, & Clifford, 2013a; Mareschal, Otsuka, & Clifford, 2014). The latter study induced uncertainty by adding luminance noise to the eye-region of face stimuli and found that observers' perception of gaze-direction was shifted towards "direct". This effect also occurred for turned heads (i.e. where head orientation and gaze direction were mismatched) presenting further support for a prior for direct gaze, rather than a shift in strategy (e.g. observers simply reporting head orientation when uncertain about gaze direction).

Perception of direct gaze, or the feeling of being "looked at", has been a focus of much research into gaze perception. For example, it has been shown that males who have high levels of social anxiety are more likely to feel they are being looked at (Jun, Mareschal, Clifford, & Dadds, 2013) and participants are better at recognising faces exhibiting direct than averted gaze (Macrae, Hood, Milne, Rowe, & Mason, 2002). Given the social significance of direct gaze and that peripheral vision guides future saccades to salient objects; it would be useful for our peripheral vision to rapidly detect being "looked at" so that possible threat can be detected. Senju and Hasegawa (2005) have also shown that presentation of a face exhibiting direct gaze delayed detection of a peripheral cue, suggesting that this is a stronger attention holding cue. Taken together these studies highlight the importance of the perception of being looked at, though how this might occur in the periphery is unclear.

Gaze direction is not derived exclusively from the eyes but also from the orientation of the head. An early example of this is the Wollaston illusion (Wollaston, 1824), where identical eyes appear to be gazing in different directions when placed in two differently oriented heads. Research into the effect of head rotation on perceived gaze direction has generally been divided into those finding that gaze direction is biased either towards the direction the head is facing (attraction) or away from the head rotation (repulsion). For example, Todorovic (2009) manipulated the eccentricity of facial features from the centre of schematic faces (i.e. shifting the eyes, nose and mouth to one side of the face), while keeping the iris eccentricity constant. It was found that shifts in face eccentricity caused the perceived direction of gaze to shift in the same direction (attraction). This effect has also been found using manipulated photographs of real faces as stimuli (Langton, Honeyman, & Tessler, 2004). In contrast to these studies that used artificial stimuli, Anstis et al. (1969) found that the perceived direction of gaze of a “looker” demonstrator was repulsed from the direction of the head.

Otsuka et al. (2014, 2015) resolved the above conflicting results by proposing a dual channel system where head rotation can exert both an attractive and repulsive effect on perceived gaze. Under this proposal the repulsive effect arises from the rotation of the eye region and the attractive effect from the global head rotation. This is based on the fact that the studies that reported attraction used stimuli where the same eyes were inserted into rotated heads, whereas those that reported repulsion used naturalistic “turned head” stimuli, where the eye region rotated with the head. In this case, head rotation causes a corresponding rotation in the eye region such that the amounts of iris and visible sclera change, leading to a shift in the perception of gaze direction. Otsuka et al. (2014, 2015) found that when only a small window around the eyes was visible, there was a clear repulsive effect of head rotation but that this effect was weaker in a whole head view condition. From this, the authors proposed a two-channel system, where rotation of the eye region exerts a strong, repulsive influence on gaze and the global head rotation exerts a weaker attractive effect, such that the overall effect is one of repulsion.

Here, we examine how people combine head-orientation and gaze-deviation when judging gaze-direction in their periphery. Peripheral vision differs from foveal vision in two essential ways: decreased spatial resolution and increased crowding. Perception in the periphery is poorer for a variety of tasks that require the recognition of fine detail, such as letter recognition (Chung, Mansfield, & Legge, 1998) and numerals (Näsänen & O’Leary, 1998). For isolated stimuli this reduction in spatial resolution is consistent with reduced cortical magnification (Duncan & Boynton,

2003) (the numbers of cortical neurons representing 1mm^2 of visual space). A quite independent limit on our peripheral vision is set by *crowding*: our inability to recognize objects, such as letters, when they are presented surrounded by "clutter". Under crowding, features of objects and clutter can be erroneously bound together resulting in object mis-identification (Dakin, Cass, Greenwood, & Bex, 2010; Mareschal, Morgan, & Solomon, 2010; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). Despite its limitations, peripheral vision allows us to effectively plan saccades by signalling the location of salient stimuli, allowing attention to then be appropriately deployed at fixation (Itti & Koch, 2000).

Most research into the processing of peripherally presented faces has focussed on observers' perception of facial emotion. Emotional information attracts attention when it is presented in the periphery (Calvo & Lang, 2005), suggesting that processing of emotion is preserved even under conditions of degraded visual acuity. Consistent with this, it has been shown that participants are quicker and more accurate at discerning the emotion of a face than its gender, when presented in the periphery (Bayle, Schoendorff, Hénaff, & Krolak-Salmon, 2011)**.** This is particularly relevant as it has been shown that whether a face's gaze is directed towards, or averted from, the perceiver modulates the emotion that is perceived (Adams Jr. & Kleck, 2005). There is a suggestion that eyes are more poorly processed in the periphery compared to other elements of the face, particularly the mouth. For example, happy emotions with a distinctive mouth expression are more easily recognized in the periphery than emotions such as fear or surprise, which are conveyed by the eye region (Calvo, Fernández-Martín, & Nummenmaa, 2014).

The perception of head and eye rotation in the periphery has been quantified in terms of an individual's ability to resolve head and eye deviations with eccentric fixation. Loomis et al. (2008) tested participants' ability to identify both head rotation and eye deviation, separately, using real face stimuli. When participants indicated the head rotation of a demonstrator using a graspable pointer, performance was near identical between 0° and 45° eccentricity and still showed a linear relationship between actual head rotation and perceived direction at 90°. In contrast, when participants had to indicate on a horizontal scale, the direction of gaze of a photo of a demonstrator's face on a computer screen, their responses tended towards direct above 8° retinal eccentricity, suggesting they were relying on the head direction (which was always direct), rather than accurately reporting the eye deviation. Although this would be expected from a reduction in spatial resolution causing a loss of fine detail around the eye region, the authors suggest there may be an additional role of crowding on peripheral processing of gaze. A recent study reports that direct gaze can be processed in the periphery without requiring attention, whereas averted directions cannot. In their study, Yokoyama et al (2014) show that participants can discriminate between a direct and an averted gaze but not between leftwards and rightwards averted while their attention is devoted to a central, letter discrimination task. However, this was performed using forward facing heads that may facilitate the processing of direct gaze and diminish that of averted gaze. A similar, more recent study has also shown limitations on peripheral processing of gaze (Palanica & Itier, 2015). The authors report that participants were quicker and more accurate at discriminating direct from averted gaze for faces viewed in the fovea compared to in the periphery. They also report a drop off in discrimination performance past 6° eccentricity. In addition, reaction times were faster when participants viewed forward facing heads with direct gaze in the periphery, suggesting an important role for head rotation in the periphery. Taken together these findings indicate that perceived gaze is not independent of head rotation but exactly how these cues interact in the periphery is unclear.

Here we measured observers' judgement of gaze direction for a range of combinations of head rotations and eye deviations (of the iris and pupil within the sclera), when viewing the face directly (central-view condition) and when the face is presented in the periphery. Given both the reduction in spatial resolution and increase in crowding that will result from peripheral presentation, we expect that the detailed information from the eye region will be lost. This could influence perceived gaze direction by changing the relative weightings of head and eye information; as eye saliency is reduced, the weighting of the eye region in combination with the global head rotation may be reduced, leading to a concomitant reduction in the repulsive bias of the eye region. We also expect that as the information from the eyes decreases, the prior for direct gaze could exert more influence on perceived gaze direction, leading to a greater number of “direct” responses. However, this only holds if the prior for direct gaze (shown for central vision) influences peripheral perception of gaze.

In order to quantify changes in performance with peripherally viewed faces, we applied a psychophysical model to the perception of gaze (Mareschal et al. 2013b). The model accounts for performance on the categorization task using three parameters: (a) the bias of perceived direct gaze (the gaze deviation that observers judge to be direct; this value is 0 if there is no bias). (b) The gaze directions at which observers respond equally either direct or leftwards/rightwards; known as the category boundaries. From these values the range of directions over which participants will perceive gaze as direct can calculated. (c) An estimate of the noise associated with the gaze perception process. Given that peripheral perception is limited by both spatial resolution and crowding we would expect an increase in noise as eccentricity increases. An increase in category boundaries as internal noise increases would be predicted by a prior for direct gaze, as gaze would be categorised as direct more often across a wider range of gaze directions under conditions of greater uncertainty.

Methods

Participants

Two authors, JF and IM, and fifteen naïve observers (undergraduates at Queen Mary University of London) participated in this experiment. All participants had normal or corrected to normal vision. Methods were approved by Queen Mary's ethics committee and participants gave written informed consent to take part in the study.

Apparatus

Stimulus presentation and data collection was controlled by a Dell XPS laptop, running MatLab software (MathWorks Ltd) with Psychophysics toolbox installed (Brainard, 1997). Stimuli were presented on a Dell LCD monitor (1440 x 900 pixels, refresh rate 60 Hz). At a viewing distance of 57cm, one pixel subtended approximately 1.8 arcmin.

Stimuli

Four synthetic, greyscale head stimuli with neutral expressions, were generated using Daz software (Daz Productions, figure 1 top row.). The heads were either forward facing or rotated to the left or to the right using FaceGen software (Singular Inversions Inc.). The original eyes were removed from the Facegen 3D models and we inserted greyscale eye stimuli created using Matlab that allowed us to control the horizontal and vertical deviations down to the nearest pixel. A small amount of vergence was added to each eye stimulus, such that the pupils in both eyes converged on a point located 57cm away (viewing distance). Face stimuli subtended on average 9 x 15 degrees of visual angle. Two female faces (one example shown in figure 1) and two male faces were used throughout the experiments.

Procedure

Gaze categorization: Five head rotations were used: forward (facing the participant), and rotated by either 15° or 30° to the left or right of participants. Below we adopt the convention of assigning leftwards (head rotations and gaze deviations) negative values. For each head rotation, nine gaze deviations were tested spanning 20° to the left to 20° to the right, in steps of 5° (i.e. -20°, -15°, -10°, -5°, 0°, 5°, 10°, 15° and 20°). Participants were required to classify the overall direction of gaze as either directed towards them, to their left or to their right. Each trial began with a grey screen presented for 200ms, then the stimulus appeared for 500ms, followed by a grey screen for a minimum of 200ms, after which point the participant responded using the 'j' 'k' and 'l' keys on the computer keyboard to indicate their responses as "leftwards", "direct" and "rightwards" respectively. The next trial began after the participant had given their response. For eccentric fixation conditions a fixation dot was constantly present, level with the centre of the face. No fixation point was presented for the centrally presented faces. Gaze offsets for each trial were determined using a method of constant stimuli. Within a run each head rotation and eye deviation combination (of the 5 x 9 = 45 possible) was presented for each of the four facial identities tested, totalling 180 faces in one run.

Eccentricity: In order to examine the effect of stimulus eccentricity, gaze categorization was measured in a central-viewing condition (observers looked directly at the face, eccentricity = 0 degree) as well as two eccentric-viewing conditions where the participants fixated on a point either (a) 6 degrees of retinal eccentricity from the centre of face (approximately 1.5 degrees to the left or right of the faces' ear) or (b) 9 degrees eccentricity from the centre of face (approximately 4.5 degrees to the left or right of the faces' ear). In the main experiment, the stimuli always appeared in the centre of the screen, with observers fixating to the left or right of the face in the eccentric viewing conditions. Participants completed three runs for each fixation condition, in a random order. Observers (apart from JF who performed all conditions) were randomly assigned to either the leftwards or rightwards eccentric condition, counterbalanced so that we obtained nine sets of data for each eccentric fixation and seventeen for the central viewing condition.

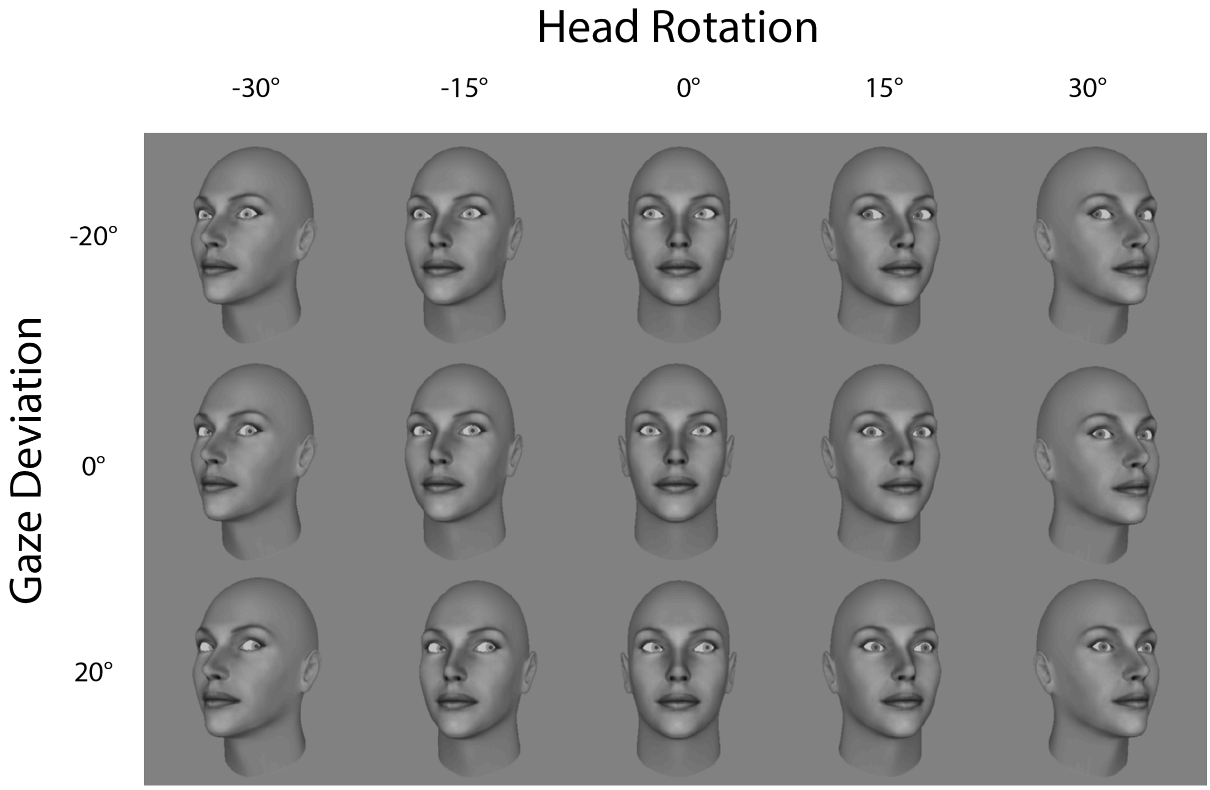

Figure 1. Sample female face displaying three head rotations and three gaze deviations. Faces were viewed centrally (central-view: eccentricity =0 degrees), and peripherally (eccentricity=±6 degrees and eccentricity =±9 degrees).

Results

1.1 Categorization of "direct" responses

Figure 2a plots the proportion of responses falling into the three response-classes, averaged across all participants and plotted as a function of gaze-deviation. Observers' responses to the gaze deviations are as follows: their "leftwards" responses are plotted in blue, their "direct" responses are in black and their "rightwards" responses are in red. Panels are arranged by varying fixation eccentricity (across rows) and head rotation (across columns). Averaged "leftwards" and "rightwards" data were fitted with logistic functions, and direct responses with a simple combination of these functions (1 minus the sum of the “leftwards” and “rightwards” functions; e.g. Ewbank et al. (2009), Mareschal et al. 2013b).

There are two main effects to note from these data: (1) when a forward facing head is viewed in the periphery, observers make “direct” responses over a wider range of gaze deviations (black curves in middle column of figure 1) and (2) when a rotated head is viewed in the periphery, observers decrease their “direct” responses (grey highlighted plots) but still respond “leftwards” and “rightwards” to the left and right gaze deviations, suggesting that they are not simply reporting the head rotation. Figure 1b highlights these points more clearly, by collapsing data across the fixation eccentricity. In this format, we show only the number of “direct” responses as a function of gaze deviation, for the different viewing conditions (y-axis) and head rotations (different panels). The non-central panels contain far fewer “direct” responses than the central panel, where we note a spreading of direct responses away from the central-viewing condition.

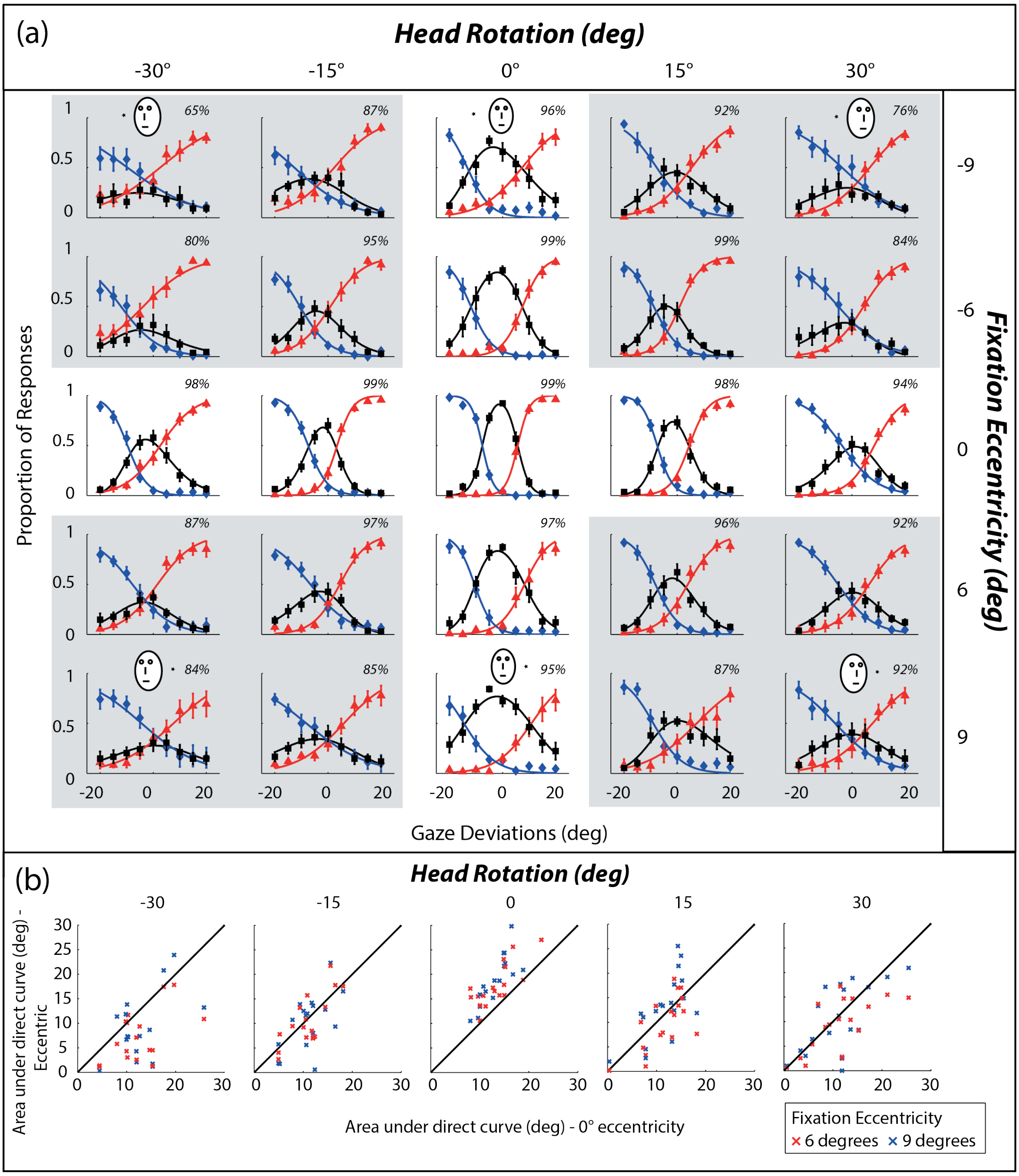

Figure 2. (a) The proportion of "leftwards" (blue diamonds/lines), "direct" (black squares/lines) and "rightwards" (red triangles/lines) responses, averaged across all participants, plotted as a function of the gaze deviation tested. Error bars represent +/- 1 S.E.M. Each column shows all data for one head rotation and each row plots all data for one fixation condition (negative values = leftward). Panels shaded grey show data collected with peripherally-viewed turned heads. Schematic insets illustrate head rotation /observer fixation combinations for the corresponding panels. Percentages show the variance explained for each model fit. (b) The area under the curve for "direct" responses, for the central-view condition (eccentricity=0 degrees) plotted against both the near (red) and far (blue) fixation conditions. The different fixation directions (left or right) are plotted in the same panel as a

function of head rotation. The black line is the line of equality; points above this have a greater AUC in the eccentric conditions than with central-presentation.

In order to quantify the changes in “direct” responses as a function of head rotation and eccentricity, we calculated the area under the curve of direct responses (e.g. area under the black curves in figure 2a). This gives us a measure of how often the participant perceived gaze to be directed towards them, across all gaze deviations. Figure 2b shows, for each participant, the area under the curve (AUC) for their central-view condition (x-axis) plotted against the AUC for both the near (red crosses) and far (blue crosses) eccentricities, for each head rotation. Data have been combined into two conditions, 6 and 9 degrees from fixation, independent of fixation side. Points above the equality line indicate that observers responded “direct” more often when the stimulus was in the periphery and data below the equality line indicate they responded “direct” less often for stimuli in their periphery.

A two way, 5x3, within subjects ANOVA was conducted to look at the effect of head rotation and retinal eccentricity on AUC for direct responses. For the purpose of this analysis (and all ANOVAs in this paper) the data from the four peripheral fixations (± 9 degrees and ± 6 degrees) were combined to create two conditions: one for 6 degrees and one for 9 degrees eccentricity, independent of fixation direction. Since there were no clear differences due to direction of fixation (t-tests comparing both the mean AUC for 6 and -6 (*t*(16)=-1.17 *p*=.259) and 9 and -9 (*t*(16)=-.36 *p*=.723) degree eccentricities were not significant) this allowed us to maintain equal group sizes across eccentricity conditions. In order to combine conditions, data were “leftwards normalised” such that a leftwards rotated head with a leftwards fixation (congruent) was combined with a rightwards rotated head with rightwards fixation (congruent). The rightwards data were flipped, e.g. a “rightwards” response to a rightwards gaze deviation of +20 degrees became a “leftwards” response to a leftwards gaze deviation of -20 degrees, maintaining the relationship between fixation direction and head rotation.

A significant main effect of eccentricity was found (*F*(2,34)=3.52 *p*=.041 η_p^2 = .171). Post-hoc Bonferroni corrected comparisons revealed that the area under the direct curve was greater for the 9 degrees eccentricity than the 6 degrees eccentricity condition (*t*(89)=-3.59 *p*=.001)), and that the other two conditions were not significantly different from each other. The assumption of sphericity was violated for both the main effect of head rotation and the interaction so a Greenhouse-Geisser correction was applied to the degrees of freedom for these two tests. A significant main effect of head rotation was also found (*F*(2.17,36.84)=24.65 *p*<0.001 η_p^2 =.592). Post-hoc Bonferroni corrected comparisons revealed that a 0° (forward) head had a significantly greater AUC than all other head rotations (0° > -30° *t*(53)=-6.64 *p*<.001, 0° > -15° *t*(53)=-7.75 *p*<.001, 0° > 15° *t*(53)=7.31 *p*<.001), 0° > 30° *t*(53)=7.34 *p*<.001)).

A significant interaction was also found (*F*(4.29,72.93) = 8.40 *p*<0.001 η_p^2 =.331). In order to investigate this interaction further, three one-way ANOVAs (for each retinal eccentricity) were conducted on head rotation. For the 0 degree eccentricity (central-view) condition there was no significant effect of head rotation on AUC (*F*(4,68) = 1.78 *p*=.144 η_p^2 =.095). For both the 6 degree (*F*(4,68)=34.83 *p*<0.001 η_p^2 =.672) and 9 degree (*F*(2.55,43.37)=17.59 *p*<0.001 η_p^2 =.508, Greenhouse-Geisser corrected) eccentric conditions a significant main effect of head rotation was found. For 6 degree eccentricity Bonferroni corrected comparisons revealed that the 0° (forward) head rotation had a significantly greater AUC than all other rotations (0° > -30° *t*(17)=-6.91 *p*<.001, 0° > -15° *t*(17)=-6.08 *p*<.001, 0° > 15° *t*(17)=8.81 *p*<.001, 0° > 30° *t*(17)=8.83 *p*<.001) and the 15° head rotation had a significantly greater AUC than both the 30° ((*t*(17)=-4.23 *p*=.001)) and -30° (*t*(17)=3.78 *p*=.001) head rotations. For the 9 degree eccentricity post-hoc, Bonferroni corrected comparisons showed that the AUC for a 0° rotated head was significantly greater than for all other head rotations

(0° > -30° (*t*(17)=-5.21 *p*<.001), 0° > -15° (*t*(17)=-4.56 *p*<.001), 0° > 15° (*t*(17)=4.80 *p*<.001), 0° > 30° (*t*(17)=5.85 *p*<.001)).

Taken together this analysis reveals that (a) for the 9 degree eccentricity conditions the AUC was greater than for the 6 degree and 0 degree conditions and that (b) the AUC for a 0° (forward) head across all eccentricity conditions was greater than for any other head rotation. The one way ANOVAs for each eccentricity reveal that the cause of these two main effects is that for eccentric fixations, the AUC is significantly greater for forward facing heads, whereas in the 0 degree eccentricity condition the AUC does not change across head rotations.

1.2. Analysis of bias

We sought to determine whether observers not only changed their number of direct responses, but also shifted these responses as a function of gaze deviation, we measured changes in their bias (e.g. what they perceive as being “direct”). In order to compare our results with Otsuka et al. (2014) (who examined bias in central vision), we recoded the data following their procedure where a direct response is attributed a value of 0.5, a left response is given a value of 0 and a right response is given a value of 1. This allows us to plot the data as a single psychometric function that contains information about the three response categories. We fit a logistic function to these data and take the bias as the gaze deviation corresponding to 50% “rightwards” responses (see Otsuka et al. 2014).

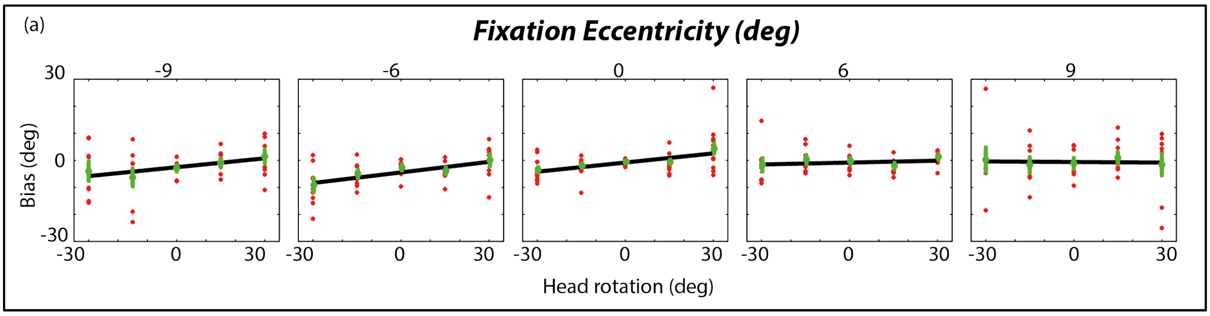

Figure 3. Data show bias in judgements of gaze direction, averaged across all participants (green circles), alongside individual data (red stars). Bias is plotted against head rotation for each fixation eccentricity. Error bars represent +/- 1 SEM. The black line is the linear regression to the mean biases.

Figure 3 plots each observer's bias (red points), alongside mean bias across observers (green). In the very few cases (N= 5 out of 425) where the logistic failed to fit observers' data, the data for the condition was excluded from the statistical analysis. A linear regression was fit to the data for each individual's biases across head rotations. Although there appears to be differences in the slopes for the leftwards and rightwards eccentric fixations, no significant differences were found between the mean gradients for the four eccentric conditions (6 degrees v -6 degrees *t*=1.79 *p*=.09, 9 degrees v -9 degrees *t*=1.15 *p*=.27). Data were therefore combined for the leftwards and rightwards eccentricities giving three eccentricity conditions. The mean of the gradients of these regression lines were compared to a line of slope zero, to determine whether there was a significant effect of head rotation on the bias. We found that for the 0 degree eccentricity condition (direct view), the mean gradient of the regression lines (0.12) was similar to that found by Otsuka et al (2014) (0.09) and was significantly greater than zero, though the effect size not large (*t*(17)=2.16 *p*=0.045 , *d*=0.5 , 95% CI=[0.02 0.24]). A positive slope is consistent with a *repulsive* effect of head turn since the bias is in the same direction as the head rotation. For example, in a leftwards turned head, a leftwards gaze deviation is judged as direct (the bias plotted here) which means that the physical gaze is being perceptually repulsed away from the head (see also Otsuka et al. 2014). The mean gradients of the two eccentric conditions did not differ from zero; however there is a (non-significant) trend for this in the periphery, suggesting that the repulsive effect of the eye region is weakened when stimuli are viewed peripherally. These results replicate those of Otsuka et al (2014) in the fovea, showing a repulsive bias of head rotation on perceived gaze direction. This same effect, however, was not demonstrated in the periphery.

1.3 CoDG model

In order to further examine the changes in performance with peripheral viewing, we fitted the model of Mareschal et al. (2013b) to each participant's data. The model has three parameters to account for an observer's performance: (a) the peak of direct gaze (the gaze deviation the observer judges most as being direct, e.g. their bias), (b) the width of their category boundaries (between direct and the two averted responses - CBW) and (c) the standard deviation of their sensory representation of gaze (assumed to have a Gaussian distribution). The width of the sensory distribution (SDN) reflects the amount of noise associated with the observers' internal representation of the gaze direction. Figure 4 plots the three parameters, across all conditions for all participants. When fitted to each individual's data, the model accounts for 77.4% of the variance in the data, whereas when fitted to the averaged data it accounts for 90.0% of the variance.

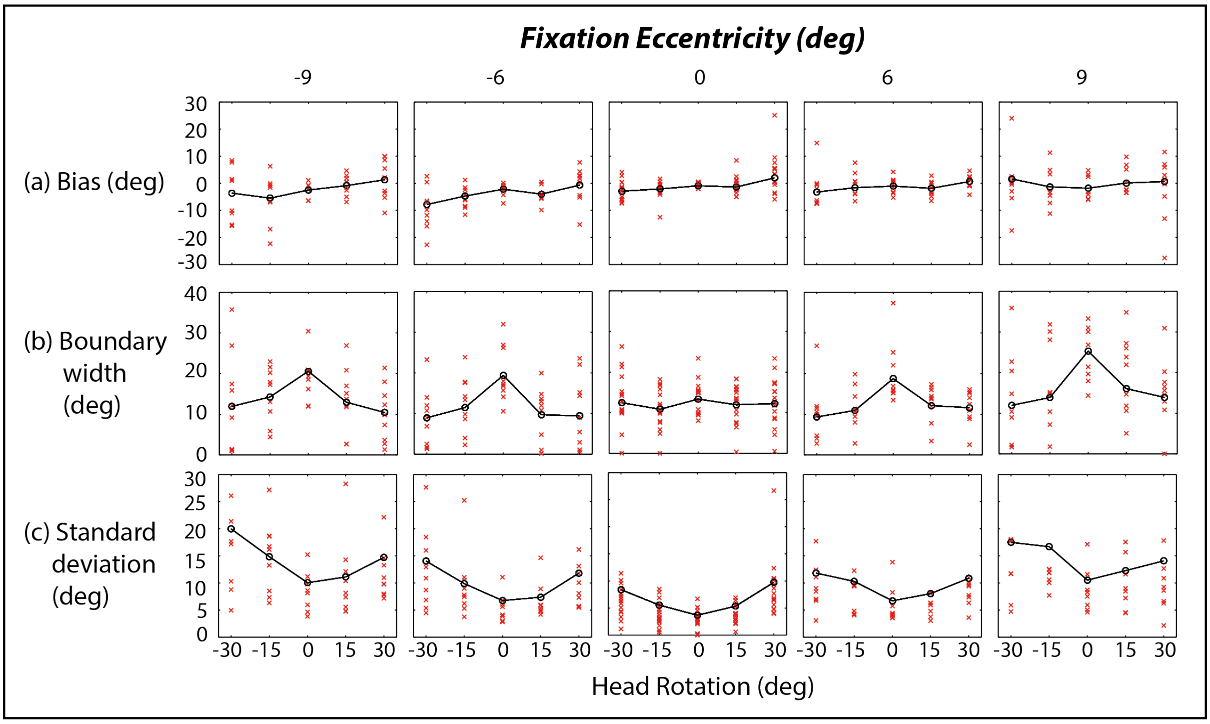

Figure 4. CoDG model parameters. Each panel plots the parameter values against head rotation for each participant (red crosses) and for the averaged data (black lines). (a) Estimates of peak (bias), (b) width (category boundaries) and (c) standard deviation of the sensory representation in the different eccentricity conditions. Each red cross is one observer.

Bias results (figure 4a) with the CoDG model are similar to the results obtained from the recoded analysis (figure 3). In order to determine how the effects of head rotation and eccentricity affected the width of the category boundaries (CBW) and the standard deviation of the internal representation of gaze (SDN), data for the far and near eccentricities were compiled as in the AUC analysis, resulting in three eccentricity conditions. Data from participants whose parameter estimates were outliers from the mean estimate (z-scores over 3) were removed for the statistical analysis (4 out of 18).

A two-way, 3x5, within subjects ANOVA was conducted on the CBW data. Significant main effects were found for eccentricity ($F(2,26)=4.873$ $p=.016$ $\eta_p^2=.273$) and head rotation ($F(4,52)=10.376$ $p<.001$ $\eta_p^2=.444$). The assumption of sphericity was violated for the interaction analysis and a Greenhouse-Geisser correction was applied. The interaction was also significant

($F(4.17,54.18)=2.653$ $p=.041$ $\eta_p^2=.169$). When a Bonferroni correction was applied to the post-hoc examination of the main effect of eccentricity, no significant differences between conditions were found. For the CBW data, post-hoc comparisons revealed wider CBW's with a 0° rotated head (forward) than all other head rotations ($p<0.05$), which did not differ from each other.

Three one-way ANOVAs were conducted on the head rotations for each eccentricity condition to look at the interaction between the variables. For the 0 degree eccentricity condition there was no significant difference between head rotation conditions. For the 6 degree eccentricity condition a significant effect of head rotation was found (Greenhouse-Geisser corrected $F(2.12,27.39)$ $p=.008$ $\eta_p^2=.306$). Post-hoc tests revealed that CBW for a 0° (forward) head was significantly greater than the -30°,-15° and 15° rotated heads (0° > -30° $t(14)=-3.54$ $p=.004$, 0° > -15° $t(14)=-5.34$ $p<.001$, 0° > 15° $t(14)=7.80$ $p<.001$); the difference between 0° and 30° was not significant. The one-way ANOVA for 9 degree eccentricity was also significant ($F(4,52)=6.06$ $p<.001$ $\eta_p^2=.318$), the CBW for a 0° head rotation was significantly greater than CBW for -15°,15° and 30° head rotations but not different to -30° (0>30 $t(14)=5.65$ $p<.001$, 0>15 $t(14)=4.7$ $p<.001$, 0>-15 $t(14)=-3.68$ $p=.003$).

The same analysis was also conducted on the SDN data. All comparisons violated the assumption of sphericity so a Greenhouse-Geisser correction was applied. Significant main effects were found for both eccentricity ($F(1.179,15.321)=38.21$ $p<.001$ $\eta_p^2=.746$) and head rotation ($F(2.152,27.975)=10.23$ p<.001 $\eta_p^2=.440$); the interaction was not significant ($F(2.28,29.68)=2.44$ $p=0.1$ $\eta_p^2=.158$). Bonferroni corrected post-hoc tests showed that the SDN for the 6 degree eccentricity condition was significantly greater than that for the 0 degree ($t(69)=-6.80$ $p<.001$) and that 9 degree eccentricity had a significantly larger SDN than the 6 degree condition ($t(69)=-7.79$ $p<.001$). Post-hoc analysis of the head rotation data revealed that the 0° (forward) head was associated with significantly less noise than all other head rotation conditions (-30° > 0° $t(41)=5.18$ $p<.001$, -15° > 0° $t(41)=5.60$ $p<.001$, 15° > 0° $t(41)=-3.80$ $p<.001$, 30° > 0° $t(41)=-6.85$ $p<.001$). As well as this, the 30° head rotation had a significantly greater noise estimate than the 15° head rotation (*t*(41)=-4.56 *p*<0.001). No other significant differences were observed.

Overall there is an increase in CBW in forward facing heads and in eccentric conditions. For all eccentric fixations, a forward facing head causes an increase in the width of the category boundaries, whereas with rotated heads the width of the category boundaries is similar to that in the 0 degree eccentricity condition (where the CBW are not affected by head rotation). This means that a forward facing head in the periphery is perceived as looking at the observer over a wider range of eye deviations than when in the fovea.

There is also an increase in the standard deviation of the internal representation of gaze direction with increasing head rotation and fixation eccentricity, meaning that observers were more uncertain in their judgements under these conditions. Interestingly, these changes are not linked to any change in the cone widths (e.g. compare panels 4b and 4c): observers categorical boundaries for judging whether a gaze is direct or averted (left or right) do not change based on an increase in the uncertainty resulting from head turn and eccentricity.

1.5 Spatial Resolution Control

In order to determine whether observers' performance in the furthest eccentric viewing condition was the result of reduced spatial resolution, we M-Scaled our original stimuli so that they were matched in spatial resolution to the 9 degrees eccentric fixation. Nine participants (3 had taken part in the main experiment) performed the categorisation task again for these centrally viewed, M-scaled stimuli. Scaling was done using the formula from Duncan and Boynton (2003): $1/M = 0.065E + 0.054$, where M is the scaling factor and E is eccentricity. The resulting stimulus subtended 3.2 x 5 degrees of visual angle.

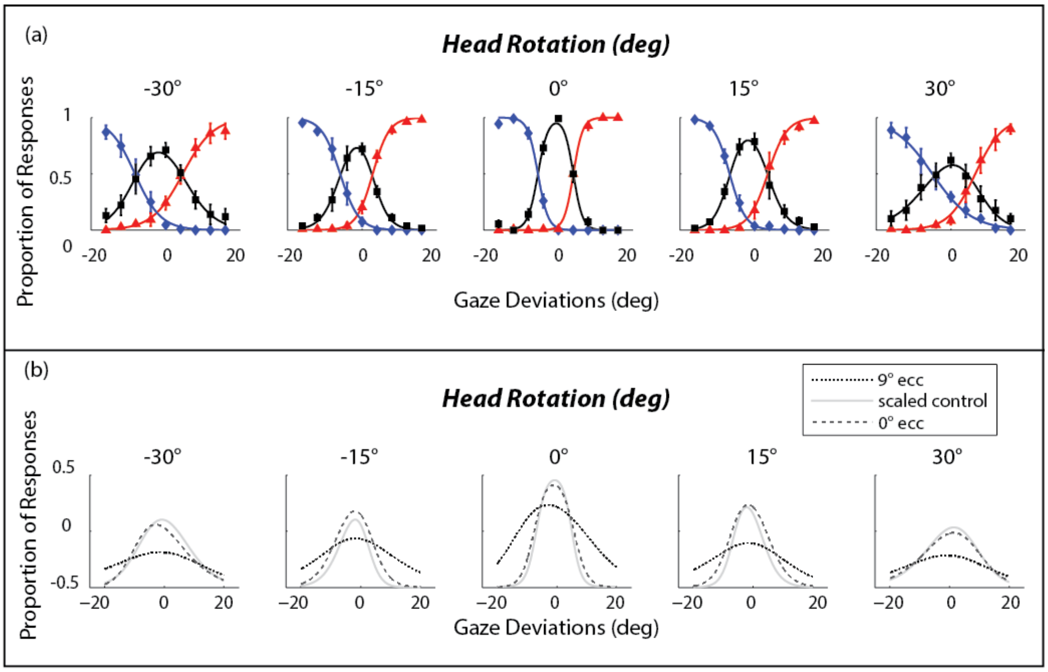

Figure 5. (a) Categorization data averaged across nine observers using M-scaled face stimuli. Each panel shows the proportion of left (blue diamonds), direct (black squares) and right (red triangles) responses to each gaze direction for a single head rotation condition. Curves are logistic fits to the data. **(b)** The "direct" curves for 0 (dashed) and 9 (dotted) degree eccentricity conditions (main experiment) and the M-scaled condition (solid grey).

Figure 5a plots responses as a function of head rotation for centrally viewed M-scaled heads. Figure 5b plots the pattern of direct responses for the scaled control, 0 degree eccentricity and the averaged far eccentric (±9 degrees) conditions. M-scaled data look very similar to the central view data in the main experiment (Fig 5b compare solid and dashed lines). In order to compare the similarity between the M-scaled data and the results from the main experiment, the sum difference between the direct curve fits for the M-scaled faces and the 0 and 9 degree eccentricities (differences in the curves in figure 5b) was calculated for each head rotation. A t-test comparing the mean difference across head rotations revealed that there was a greater average difference between the M-scaled and 9 degree eccentric stimuli than the scaled and 0 degree eccentric stimuli ($t(8)=2.86$ $p=0.02$), suggesting that performance in the periphery is not solely due to changes in spatial resolution.

Discussion

Using a categorization task we find that observers' perception of gaze direction depends both on head rotation and viewing eccentricity. We find that when the stimuli are viewed foveally (direct-view condition), gaze is categorized as "direct" over a broad range of gaze deviations, consistent with earlier reports (e.g. Gamer & Hecht, 2007). We also find evidence of a repulsive effect of head rotation that is displayed by the peak of the direct responses occurring at a gaze deviation in the *same* direction as the head rotation. For example, if the peak of direct gaze (i.e. perceived 0°) for a leftwards rotated head is also leftwards (e.g. -3° degrees), this means that the perceived gaze deviation is repulsed away from the head rotation (away from -3° towards 0°), in accordance with the results of Otsuka et al. (2014, 2015).

Using M-scaled foveal stimuli, we have also demonstrated that the changes in peripheral gaze perception are not solely the result of reduced spatial resolution in the periphery. This does not rule out the possibility of other limits on the processing of the gaze direction of peripheral faces, such as crowding. As can be seen from the model estimates of the internal noise on the representation of gaze direction, peripheral faces are associated with more uncertainty than foveal ones.

When stimuli were presented in the periphery, the head rotation largely determined whether the observer classified gaze as direct. When the head was forward facing, the overall number of direct responses increased and the range of eye deviations that were classified as direct also increased. This suggests that the perception of being looked at in the periphery seems to be driven by a head that is forward facing, rather than by any particular cue from the eyes. When heads were rotated, the opposite occurred, with direct responses reducing across all gaze deviations. This result cannot simply be attributed to participants' reporting the direction of head turn, as the 'left' and 'right' responses were not correspondingly affected (e.g. observers never responded only left with a leftwards rotated head and vice versa).

Previous research has suggested that an increase in the uncertainty associated with the processing of a (foveally viewed) face leads to more gaze deviations being perceived as direct (Mareschal, Calder, & Clifford, 2013b; Mareschal, Otsuka, & Clifford, 2014). Here, we find that the increase in uncertainty due to the face being processed peripherally led to an increase in direct responses for a forward facing head only. When heads were rotated, direct responses were greatly reduced. Although this is not immediately surprising (since the rotated heads never pointed directly at the observer), a few points emerge. (1) Even with gaze deviations that could combine with a rotated head to sum to direct (e.g. -15 degree head rotation with a 15 degree gaze deviation), observers rarely classified this as direct, suggesting that gaze deviation and head rotation don't simply add when presented in an observer's periphery. (2) Given that we report an increase in uncertainty with head rotation in the periphery, this suggests that the prior for direct gaze, shown to exist in central vision with both forward facing and rotated heads, does not hold in the same way in the periphery. It may be that in the periphery other influences (such as, for example, a prior for head rotation) may dominate observers' performance. Given the limits of peripheral vision, it is possible that a prior for "direct" *head* rotation rather than gaze direction (e.g. an increased perception that head rotation is facing the observer), may exist in the periphery. Given the suggestion that forward facing heads attract attention (e.g. Palanica & Itier 2015), a prior for direct head rotation may facilitate the shift in attention to a "direct" head so that the true direction of gaze can be more accurately perceived.

Our results highlight the overriding importance of a forward facing head in the periphery. It has been suggested that two components influence head rotation processing; the symmetry of the outline of the head and the orientation of the nose (Wilson, Wilkinson, Lin, & Castillo, 2000), both of which can be used independently of each other (Langton et al., 2004). Wilson et al. (2000) report that - for centrally viewed stimuli - the average head orientation threshold is low (at around 1.9°), although this increased when discrimination was performed on heads rotated by 30°. For peripherally viewed stimuli, Loomis et al (2008) found that a high level of sensitivity to head orientation was maintained as far as 90° retinal eccentricity, whereas eye gaze deviation was only accurate to 4° eccentricity (from the closest eye). Our results suggest that observers' may perform some form of a symmetry judgement on the head in the periphery. Given that neurons in the periphery are preferentially tuned to low spatial frequencies (Movshon et al. 1978), these could provide a means for a symmetry judgement, akin to the (large) V4 units proposed by Wilson et al. (2000) in their model of head orientation judgments. Alternatively it has been proposed that the spatial arrangement of internal features allows for direct judgements of facial-symmetry through the use of low spatial frequency horizontal information (Dakin & Watt, 2009).

One intriguing suggestion arising from these results is that of a cascade of information processing, whereby firstly the head outline is assessed as either symmetrical (e.g. forward) or non-symmetrical and then this information influences the width of the category boundaries used to determine whether gaze is direct or averted. For example, if a head is forward facing, it may be that we assume that we are being looked at and therefore don't actively process the gaze. This is consistent with the recent finding that the recognition of direct gaze in the periphery (using forward facing heads) doesn't require attention (Yokoyama et al. 2014). In this case, it may well be that the head cue is processed rapidly and that the observer doesn't make use of the finer information required to process gaze, but simply responds "direct". If so, we predict that response times for categorizing gaze in forward facing heads in the periphery would be faster than when gaze categorization is measured using rotated heads, a finding that has recently been reported by Palanica and Itier (2015).

Our results suggest that discrimination between leftwards and rightwards gaze, particularly in averted heads in the periphery, is still good even out to 9° eccentricity (e.g. fig. 2 bottom left/right panels). This may seem in conflict with reports that gaze discrimination performance falls off between 4° (Loomis et al. 2008) and 6° (Palanica and Itier 2015) eccentricity. However, these differences may simply reflect methodological differences. Loomis et al. (2008) required participants to respond by selecting a number from a range of directions presented in front of them. They report that for stimuli beyond 4° eccentricity, responses were more clustered around direct and did not correspond to the gaze direction presented (reduced accuracy). However, they used forward facing heads for all their stimuli; given our finding that gaze in peripherally viewed forward facing heads is classified as direct over a wide range of gaze deviations, this may explain why most of their responses clustered around direct. More recently, Palanica and Itier (2015) report an increase in discrimination errors between direct and averted gaze for peripherally viewed faces when head rotation and gaze deviation are incongruent (e.g. frontal heads with averted gaze and deviated heads with direct gaze). This is largely consistent with our results; in forward facing heads with leftwards (rightwards) deviated gaze, our observers respond left (right) less often, and in deviated heads with direct gaze, observers respond direct less often. In both cases, this corresponds to an increase in error rate, consistent with Palanica & Itier (2015). Our results differ in that our participants were still able to discriminate between direct and averted at 9° eccentricity, however this may be because Palanica and Itier (2015) presented stimuli briefly (150ms) and required a speeded response, which could have led observers to use the head direction cue, increasing error rates.

The results for the bias using heads in direct (foveal) view show a repulsive effect of head rotation on gaze perception, such that perceived direction of gaze is shifted away from the head rotation. This is consistent with previous findings that head rotation exerts a repulsive influence on gaze direction, mainly due to configural effects of the eye region (Otsuka et al., 2014, 2015). As noted by Anstis et al. (1969) the most notable change in the eye region is the ratio of sclera on either side of the iris when a head rotates. It is likely that this is the cue used to discern the rotation of the eye region that exerts a repulsive effect on perceived gaze direction. Though some studies have reported an attractive effect of head rotation, these either used forward facing eyes inserted into turned heads (Langton et al., 2004; Todorović, 2009) or were confounded by the lighting conditions (Cline, 1967).We do not find a significant repulsive effect of head rotation in the periphery, though there is a potentially interesting (non-significant) difference between the leftwards and rightwards fixation sides (figure 3). The reduction in the bias is most likely due to the changes in weighting of the cues from the head and the eye region. The attractive cue of head rotation (mainly carried by low spatial frequency information, e.g. Wilson et al. 2000) is likely to more strongly influence judgements in the periphery, whereas the repulsive cue of the eye region (requiring higher spatial frequency) would be weakened since resolution decreases with viewing eccentricity.

One function of peripheral vision is to process information in order to plan future saccades (Henderson, 2003). It appears that direct gaze, known to be a strong attention holding stimulus (Senju & Hasegawa, 2005), may have a different effect in the periphery. Our findings suggest that a forward facing head with averted gaze may be more likely to attract attention than a turned head with a physically forward (direct) gaze. These results have interesting repercussions for certain clinical populations for whom direct gaze has been reported to be aversive (e.g. socially anxious or autistic people (Senju & Johnson, 2009; Wieser, Pauli, Alpers, & Mühlberger, 2009). It is possible that forward pointing faces, viewed in their peripheral vision, might actually exacerbate their sense of being looked at.

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