Vision Research 131 (2017) 67–74

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The center of attention: Metamers, sensitivity, and bias in the emergent perception of gaze

Timothy D. Sweeny [a,*], David Whitney [b,c]

[a] Department of Psychology, University of Denver, United States
[b] Vision Science Group, University of California – Berkeley, United States
[c] Department of Psychology, University of California – Berkeley, United States

A R T I C L E I N F O

Article history:
Received 22 July 2016
Received in revised form 17 October 2016
Accepted 19 October 2016
Available online 10 January 2017

Keywords:
Gaze perception
Face perception
Emergent
Categorical perception
Eyes

A B S T R A C T

A person's gaze reveals much about their focus of attention and intentions. Sensitive perception of gaze is thus highly relevant for social interaction, especially when it is directed toward the viewer. Yet observers also tend to overestimate the likelihood that gaze is directed toward them. How might the visual system balance these competing goals, maximizing sensitivity for discriminating gazes that are relatively direct, while at the same time allowing many gazes to appear as if they look toward the viewer? Perceiving gaze is an emergent visual process that involves integrating information from the eyes with the rotation of the head. Here, we examined whether the visual system leverages emergent representation to balance these competing goals. We measured perceived gaze for a large range of pupil and head combinations and found that head rotation has a nonlinear influence on a person's apparent direction of looking, especially when pupil rotations are relatively direct. These perceptual distortions could serve to expand representational space and thereby enhance discriminability of gazes that are relatively direct. We also found that the emergent perception of gaze supports an abundance of direct gaze metamers—different combinations of head and pupil rotations that combine to generate the appearance of gaze directed toward the observer. Our results thus demonstrate a way in which the visual system flexibly integrates information from facial features to optimize social perception. Many gazes can be made to look toward you, yet similar gazes need not appear alike.

1. Introduction

Perceiving a person's gaze direction is critical for understanding and predicting their behaviors and intentions (Allison, Puce, & McCarthy, 2000; Baron-Cohen, Campbell, Karmiloff-Smith, Grant, & Walker, 1995; Itier & Batty, 2009). Perceiving when a person is looking directly at you is particularly important because it is a strong predictor that a social interaction may occur (Emery, 2000). Accordingly, the visual system has developed notable sensitivity for perceiving direct gaze (Cline, 1967). Direct eye contact is represented by distinct visual mechanisms (Calder, Cassel, Jenkins, & Clifford, 2008), it is detected faster than averted gaze (Senju, Kikuchi, Hasegawa, Tojo, & Osanai, 2008), and it uniquely captures visuo-spatial attention (Senju & Hasegawa, 2005). This sensitivity is in place even during childhood. For example, infants look at faces with direct eye gaze longer than faces with indirect gaze (Farroni, Csibra, Simion, & Johnson, 2002), children are more sensitive to horizontal compared to vertical pupil displacement at the age of eight (Vida & Maurer, 2012), and infrequent exposure to direct eye contact early in life is known to disrupt typical deployment of spatial attention during communication (Senju et al., 2015).

Despite their importance, or perhaps because of it, people tend not to see relatively direct gazes exactly as they are. That is, people tend to overestimate the likelihood that others are looking towards them under conditions of perceptual uncertainty (Clifford, Mareschal, Otsuka, & Watson, 2015; Mareschal, Calder, & Clifford, 2013), but they also underestimate the likelihood that gaze is direct when information from a face is clearly visible (Anstis, Mayhew, & Morley, 1969; Otsuka, Mareschal, & Clifford, 2016). The visual system thus appears to be faced with a pair of competing challenges. First, representational space should be expanded for gazes that are relatively direct, as these are the kinds of gazes that are arguably the most important. Such a

* Corresponding author at: University of Denver, 2155 S. Race St, Denver, CO 80210, United States.
E-mail address: timothy.sweeny@du.edu (T.D. Sweeny).

http://dx.doi.org/10.1016/j.visres.2016.10.014
0042-6989/

design would make subtle differences between gazes near the category boundary of left/right appear more distinct and thus easier to discriminate. Second, the visual system should accommodate a prior for seeing direct gaze often and allow many gazes to appear as if they look toward the viewer—a direct gaze bias. This bias would ensure that when gaze is direct (or nearly direct), it is seen as such. In other words, people should be good at perceiving relatively direct gazes, yet at the same time misperceive many gazes as direct. Here, we examine how emergent gaze representation may distort the appearance of a person's direction of looking, and thus allow the visual system to balance these seemingly contradictory goals.

Although altering a feature's appearance to improve perception may seem paradoxical, this process can actually be beneficial when that feature has a value near a category boundary. As long as the distortion is systematic, it can decrease the opportunity for random sensory noise to cause across-category perceptual errors (Kourtzi, 2010). Indeed, the visual system often sharpens perception around category boundaries (Ball & Sekuler, 1980, 1982; Bornstein & Korda, 1984; Etcoff & Magee, 1992; Ferrera & Wilson, 1990; Harnad, 1987; Heeley & Buchanan-Smith, 1992; Liberman, Harris, Hoffman, & Griffith, 1957; Matthews & Welch, 1997), and this sensitivity in turn produces perceptual distortions. For example, discrimination of biological motion is best for direct trajectories, and this sensitivity repels the perceived walking direction of a person away from the leftward/rightward category boundary (Sweeny, Haroz, & Whitney, 2012). Similar distortions enhance the perception of local motion trajectories (Rauber & Treue, 1998), facial identity (McKone, Martini, & Nakayama, 2001), and multi-modal perception of gender (Smith, Grabowecky, & Suzuki, 2007). We predicted that similar kinds of mechanisms would influence the perception of gaze, but not just the local perception of pupil rotation. Rather, we expected perceptual distortions to emerge at the level of emergent gaze, when a person's direction of looking is determined not just by the rotation of the pupils within the aperture of the eye, but the face and head as well.

Gaze is perceived by integrating local information from the eyes with the rotation of the head. This interaction produces a striking percept—the Wollaston effect—where a person's perceived gaze direction is pulled by the rotation of the head (Cline, 1967; Kluttz, Mayes, West, & Kerby, 2009; Langton, Honeyman, & Tessler, 2004; Murayama & Endo, 1984; Otsuka, Mareschal, Calder, & Clifford, 2014; Wollaston, 1824). The perceived gaze that results form this integration is carried neither by the pupils nor by the head alone, and thus has a unique quality. We refer to this distinct percept as emergent gaze. Very recently, an investigation conducted in parallel with our own showed that, at least in some circumstances, this integration is the result of a linear combination of information from the head and eyes (Otsuka et al., 2016). Here, using a design with some notable differences, we tested the hypothesis that the visual system leverages this integrative process to simultaneously enhance representation of relatively direct gazes, and at the same time, allow many kinds of gazes to appear to be direct. First, we predicted that head rotations would distort perceived gaze most strongly when pupil rotations are relatively direct, thereby expanding representational space for discriminating the most important kinds of gazes. And since sensitivity for discriminating head rotation peaks near the left-vs.-right category boundary (Wilson, Wilkinson, Li-Ming, & Castillo, 2000), we predicted that head rotations near this boundary would exert a particularly strong pull on perceived gaze. Second, we predicted that the increased range of gaze percepts that result from these emergent distortions should also produce an abundance of direct gaze metamers—different combinations of head and pupil rotations that combine to generate the appearance of gaze directed at the observer.

2. Experiment 1

2.1. Materials and method

2.1.1. Observers

Nine observers (eight naïve) provided informed consent. All had normal or corrected-to-normal visual acuity and were tested individually in a dimly lit room. All work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.2. Stimuli

We manipulated gaze at the level of an emergent feature, in which a person's apparent direction of looking is determined by integrating local pupil information with the rotation of the head (Wollaston, 1824). Fig. 1 illustrates one example of this phenomenon. Here, the rotations of the irises/pupils within the apertures of each pair of eyes are identical, yet they appear to have leftward or rightward gazes by virtue of being superimposed onto heads with subtle leftward or rightward rotations, respectively. We note that internal features, like the nose, are sufficient for discriminating head rotation (Wilson et al., 2000) and produce strong attractive effects on perceived gaze (Langton et al., 2004). We also note that this attractive effect from the head is distinct from a separate effect that emerges from the appearance of the eyes (Anstis et al., 1969; Gibson & Pick, 1963; Mareschal et al., 2013). When a head turns, the size and shape of one eye's aperture appears to change more quickly than the other's, at least from the perspective of the viewer, and this change influences the perception of the iris and pupil within that aperture. Unlike a head rotation in the same direction, this change in local information from the eyes actually repels the perceived direction of gaze. These attractive and repulsive effects from the head and eyes are likely to be related and potentially complementary (Otsuka et al., 2014, 2016), and the extent to which one dominates the other likely depends on the relative visibility of information from the head or eyes (Gamer & Hecht, 2007). For simplicity we focus here on the attractive effect from the rotation of the head. In particular, we use stimuli reminiscent of those from Wollaston's original investigation of gaze (Wollaston, 1824) and several others thereafter, where the shape and size of the eye apertures never change despite rotation of the head.

We aimed to examine the perception of gaze across a wide range of head and pupil rotations. We thus created a set of 144 computer-generated faces by independently manipulating head rotation and pupil rotation (Face Gen Modeller, Version 3.5.5, Singular Inversions, 2009). First, we created heads with nine degrees of horizontal rotation (−8°, −6°, −4°, −2°, 0°, +2°, +4°, +6°, and +8°; turning from the observer's left to right, respectively). Next,

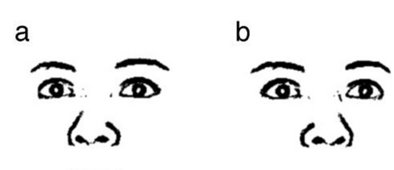

Fig. 1. Eyes with identical pupil rotations appear to have unique gaze directions when coupled with (a) leftward or (b) rightward head rotations. Note that, in both images, the shapes of the scleras (the white regions of the eyes) and the positions of the pupils and iris' within the scleras are identical. The shading information nearby the eyes, as well as the eyebrows, noses, and mouths was allowed to vary.