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# Geometrical basis of perception of gaze direction

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**Abstract**

Perception of gaze direction depends not only on the position of the irises within the looker's eyes but also on the orientation of the looker's head. A simple analysis of the geometry of gaze direction predicts this dependence. This analysis is applied to explain the Wollaston effect, the Mona Lisa effect, and the newly presented Mirror gaze effect. In an experiment synthetic faces were used in which the position of the iris and the angle of head rotation were varied. Different groups of subjects judged iris position, head rotation, and gaze direction of the same stimuli. The results illustrate how cues of iris location and head orientation interact to determine perceived gaze direction.



*Keywords:* Gaze direction; Mona Lisa effect; Wollaston effect

## 1. Introduction

How does an observer judge where a 'looker' is looking? One intuitively obvious and simple cue of gaze direction is what I will call *iris eccentricity*: this is the relative position of the irises within the portion of the sclera visible through the eye openings of the looker. A number of authors have suggested a predominant role for iris eccentricity in the determination of gaze direction. For example, Emery (2000) claimed that 'gaze following can be performed using a simple rule (dark in the center of the eye equals eye contact; dark to the left of the eye equals looking left; dark to the right of the eye equals looking right)' (p. 585). Baron-Cohen (1994) envisaged a system that 'tracks and codes the spatial position of the d[ark] region relative to the w[hite] region' (p. 519). Symons, Lee, Cedrone, and Nishimura (2004) also stressed the role of the 'dark-white configuration' of the looker's eyes (p. 452). Anstis, Mayhew, and Morley (1969) stated that 'judgments of direction of gaze are determined principally by the position of the pupil in the visible part of the eye' (p. 489). Perrett, Hietanen, Oram, and Benson (1992) suggested that while in some circumstances, such as when the eyes of a looker are poorly visible, the looker's head or body orientation may serve as cues for gaze direction, under favorable observation conditions such information is overridden by iris location cues, through neural inhibition. Ganel, Goshen-Gottstein, and Goodale (2005), while not invoking iris eccentricity explicitly, wrote that in contrast to the processing of expression, which 'seems to be based on configural analysis of the entire face ... the processing of direction of gaze ... seems to be based on part-based analysis, one that is probably based on the region of the eyes' (p. 1196).

In this paper I will first criticize the notion that iris eccentricity information alone suffices to adequately register gaze direction, and will then present a simple geometric analysis, stressing the combined roles of iris eccentricity and head orientation in determining gaze. Next, I will describe three gaze perception phenomena and show how they can be accounted for on the basis of such geometry. Finally, I will report an experiment supporting the analysis.

### 1.1. Three simple demonstrations

It is easy to show that relying on iris eccentricity alone only works under restricted conditions, and cannot serve as a general strategy for accurate detection of gaze

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direction. For the first demonstration, suppose that a looker faces you directly and shifts her gaze from left to right, moving the irises from one end of the eye opening to the other. In this case 'dark in the center' of the looker's eyes does indeed correspond to eye contact, and other iris positions systematically correspond to other directions, for which the looker's gaze misses the observer. However, this correlation of iris position and gaze direction only holds if the looker's head is oriented frontally with respect to the observer. In the second demonstration, suppose that the looker turns her head about its vertical axis (as in gesturing 'no'), but keeps looking at you throughout, compensating her head turns by oppositely directed eye turns. Note that while doing so her irises will make much the same sorts of displacements relative to the eye openings as in the first demonstration; nevertheless, eye contact will be maintained throughout. All this can be easily checked by looking at yourself in the mirror while gesturing 'no'. Note in particular that for strongly angled head orientations the irises are located far from the center, almost in the corners of the eye openings, and yet you have a vivid impression that the face in the mirror looks straight at you. For the third demonstration, suppose that the looker again turns her head but keeps her irises centered in the eye openings, as if she were a statue. In this case eye contact with the observer will only occur when her head is oriented frontally. In sum, although iris eccentricity correctly predicts gaze direction when the looker's head frontally faces the observer, for other head orientations eye contact need not be based on centered irises, nor do centered irises necessarily imply eye contact.

### 1.2. Studies of gaze perception

Several studies have confirmed that perception of gaze direction is affected by the looker's head orientation (Anstis et al., 1969; Cline, 1967; Gibson & Pick, 1963; Langton, 2000; Langton, Honeyman, & Tessler, 2004; Maruyama & Endo, 1983; Seyama & Nagayama, 2005). Such investigations can be divided into two groups. One group involved studies of accuracy of gaze detection. Their general result is that judgments of gaze direction are quite accurate for lookers with frontally oriented heads, but that biases arise when their heads are angled. As noted by Langton, Watt, and Bruce (2000), such biases generally can have two directions. When the looker's head is turned away from the frontal orientation, such that it faces leftwards or rightwards (from the observer's point of view), then perceived gaze direction may, in principle, be biased away from the veridical value in the *same* direction as the head angle (being shifted rightwards for rightwards head angles and leftwards for leftwards head angles) or in the *opposite* direction (being shifted rightwards for leftwards head angles, and vice versa). Biases in the opposite direction were reported by Gibson and Pick (1963), Cline (1967), and Anstis et al. (1969). This is an interesting phenomenon whose basis may lie in biased registration of spatial attributes of curved surfaces, such as the face and the sclera, from projectively foreshortened stimuli (see Langton et al., 2000). However, my interest here concerns reports of biases in the same direction as the head turn (Langton et al., 2004; Maruyama & Endo, 1983). I will argue that such effects are not necessarily perceptual illusions, but can be predicted from a simple geometrical analysis of gaze direction, provided below.

A second group of studies involved reaction time measurements for judgments of gaze direction. It was found that reaction times are shorter when the eyes and the head are turned in the same direction than when they are turned in different directions (Langton, 2000; Seyama & Nagayama, 2005). Such and related findings can be interpreted to show that the visual system uses head orientation as a secondary source of information about gaze direction, in addition to and parallel with iris eccentricity; these two sources may either be congruent or incongruent, leading to corresponding acceleration or deceleration of gaze processing. However, I will argue on geometrical grounds that the roles of iris eccentricity and head orientation are different, and that they are not two separate, potentially independent sources of gaze direction; rather, both of them are necessary and neither is sufficient for its determination. Furthermore, I will claim that this geometrical analysis can provide the basis for the explanation of three intriguing gaze perception phenomena, two well-known and one new.

Gaze direction can be studied both for live 3-D lookers and 2-D portraits. The three phenomena that I will discuss as well as the experiment I will report involve only 2-D portraits. However, no qualitative distinctions between the two cases have been reported in the literature. The papers which have included both conditions (Symons et al., 2004; Yoshida, Kamachi, Hill, & Verstraten, 2005) have found only quantitative differences, which may be due to richer cues for head orientation in the 3-D case.

### 1.3. Geometry of gaze direction

Gaze direction is the vector positioned along the visual axis, pointing from the fovea of the looker through the center of the pupil to the gazed-at spot; binocular looking involves two such vectors, but for simplicity I will disregard here the fact their directions are somewhat different. Like any other spatial direction, direction of gaze must be defined with respect to some reference frame. One potential source of conceptual confusion here is that there are several possible reference frames, and thus several different variants of the notion of gaze direction. One variant is *looker-related* gaze direction: this is the direction of gaze as determined in relation to the looker's head, specified by the rotational state of the eyeball with respect to the skull. Centered irises do not generally signify eye contact but rather the fact that the looker is looking *straight ahead*, which is the direction approximately perpendicular to the frontal plane of the looker's own head; turning the eyeballs to other positions corresponds to various gaze directions deviating from straight ahead. The second way to define gaze direction is in the form of *environment-related* gaze direction: this is the direction of gaze specified with respect to some environmental reference frame. Any environmental object can serve as such a reference frame, but a particularly important special case is *observer-related gaze direction*: this is the direction of the looker's gaze with respect to *me*, the observer (who from the looker's point of view is just a part of the environment). The most important distinction in this case is whether the looker looks at me or not.

Given the multiplicity of possible reference frames, asking a question such as 'where is the looker looking?' can have different types of answers: looker-related (such as 'straight ahead'), observer-related (such as 'to my right', where 'my' refers to the observer), and environment-related but observer-independent (such as 'at the window'). Furthermore, a statement like 'the looker's gaze is averted' is ambiguous and potentially confusing, since it can mean either 'averted from the looker's straight ahead' (thus necessarily involving non-centered irises) or 'averted from the observer' (which may involve either centered or non-centered irises); if the looker's head is frontally oriented with respect to the observer then the two meanings of the statement agree with each other, but if it is angled, one may be true and the other false. Note that in everyday circumstances the observer will most likely not be concerned with where the looker looks with respect to herself, but rather what she looks at in the environment, and in particular whether or not she looks at the observer. Knowing the target of the looker's gaze is useful to the observer because it provides valuable hints about current attention, possible intention, and potential action of the looker (Langton et al., 2000).

Whatever the reference frame, gaze direction as a vector is an imaginary line in space, unobservable as such, and needs optical cues to be visually registered. Iris eccentricity is a very good indicator of looker-related gaze direction, since any particular position of the eyeball corresponds with a particular position of the iris relative to the eye opening. However, iris eccentricity alone is not a reliable indicator of environment-related gaze direction. This is simply because the head is mobile, and when it turns the eyes turn with it and change their orientation with respect to the environment; however, this change is not reflected in the relative position of the iris in the eye opening, because the eye opening itself also turns with the head. One way to specify environment-related gaze direction is as a combination of (a) the orientation of the looker's eyes with respect to her head and (b) the orientation of the looker's head with respect to the environment. For example, in order to gaze at an object that lies 30° towards right, the looker can turn her head 20° towards right, and then turn her eyes 10° to the right of her straight ahead.

In the following I will mainly be concerned with observer-related gaze direction. In this case, determining the environmental orientation of the looker's head involves specifying her head turn *with respect to the observer*. Expressed in angular terms, observer-related gaze direction (whose spatial angle will be denoted as $\gamma$) is simply the additive combination of observer-related head orientation ($\kappa$) and looker-related gaze direction ($\lambda$):

$$\gamma = \kappa + \lambda \tag{1}$$

Within this format, 'looking at me' can be expressed by the condition:

$$\kappa + \lambda = 0 \tag{2}$$

This relation is satisfied in the second demonstration above, in which head orientation ($\kappa$) in one direction is balanced by eye turn ($\lambda$) in the opposite direction, keeping observer-related gaze direction ($\gamma$) constant at zero (with 'me' located at the origin of this 'observer-centered' co-ordinate system).

### 1.4. Geometrical basis of perception of gaze direction

So how does an observer judge where a looker is looking? Given the above considerations, a plausible hypothesis is that perception of gaze direction is based on information not only about the eye turn but also about the head turn of the looker (see Langton et al., 2004; Wilson, Wilkinson, Lin, & Castillo, 2000). Thus variations of perceptual cues of both eye and head orientation should affect perceived gaze direction, and the directions of these effects should generally agree with the above geometrical relation of the corresponding angles. Such an approach was assumed in the pioneering work of Gibson and Pick (1963), who proposed that the perception of 'being looked at' involves lookers for who 'the asymmetry of the projected face is equal and opposite to that of the projected eyes' (p. 389). Eq. (2) is a formal version of the geometrical basis of this proposal. The fully symmetrical case, in which $\kappa = \lambda = 0$, corresponding to centered irises in frontal heads, is just one, though salient way to fulfill this condition. In the following I will argue that some intriguing gaze perception phenomena can be understood within the framework of this rather simple analysis.

### 1.5. Three phenomena of gaze direction

The fact that iris eccentricity alone does not necessarily specify gaze direction was first demonstrated by Wollaston (1824). A variation on his demonstrations is presented in Fig. 1.[1] It involves a well-known original image (Fig. 1a) and two transformations, which illustrate the effects of iris eccentricity (Fig. 1b) and head orientation (Fig. 1c) on perceived gaze direction. Note that the irises in the original image are strongly off-centered, that is, averted from straight ahead in the looker-related sense, but that there is an impression that the portrait gazes in the general

[1] Shinki Ando independently also used the Mona Lisa for an illustration of the Wollaston effect.

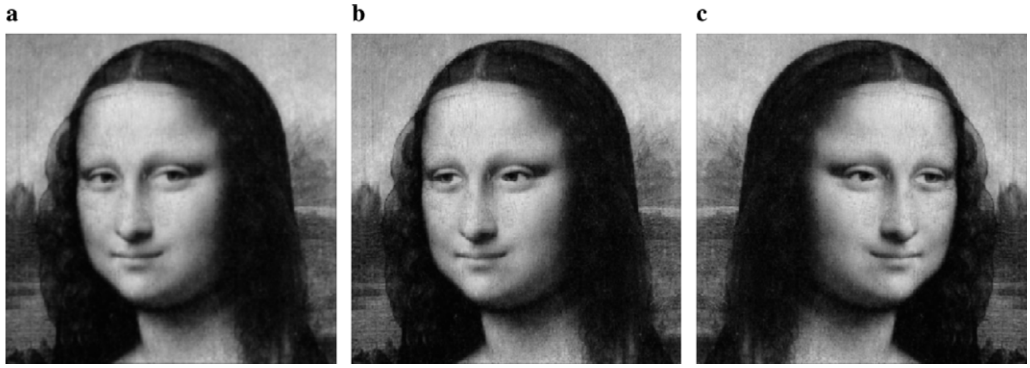

Fig. 1. The Wollaston effect: perceived gaze direction of a portrait depends not only on the position of the irises but also on the orientation of the head. (a) Original image: irises shifted rightwards, head turned leftwards. Result: gaze directed at observer. (b) Manipulating eye turn: irises shifted leftwards, head turned in the same direction as in original. Result: leftwards shift of gaze, compared to original. The eyes in this portrait are the mirror images of the original eyes. (c) Manipulating head turn: head turned rightwards, irises in the same positions as in the original. Result: rightwards shift of gaze, compared to original. Note that this image is simply the mirror image of (b).

direction of the observer. The Wollaston effect is illustrated by the fact that the two portraits in Figs. 1a and c have equal iris eccentricities, but are perceived to gaze in quite different directions.

Although discovered long ago, the Wollaston effect appears to have re-entered the literature only relatively recently, and has not yet received much attention (see Bruce & Young, 1998; Langton et al., 2000, 2004; Wade, 1998). Bruce and Young (1998) wrote that this effect shows that 'even though our ability to perceive gaze direction is highly skilled, it is not infallible', and commented that 'the effect would repay further investigation to establish just why this happens' (p. 212), thus characterizing it as an as yet unexplained perceptual illusion. An empirical study of the effect was performed by Langton et al. (2004, especially experiment 1A). They used face stimuli with irises that were either centered (a condition they called 'direct gazes'), or shifted leftwards or rightwards within the eye opening (called 'averted gazes'), which were pasted upon heads that were either facing the observer or were oriented at an angle. The task given to the subjects was 'to judge whether the eyes were averted or were looking directly at them' (p. 756). The authors wrote that they were 'successful in inducing a Wollaston-type illusion in their participants', in that many of their judgments were non-veridical, involving 'illusory shifts of both direct and averted gazes', because head turns had the effect of 'making averted gazes appear to be direct and direct gazes appear to be averted' (p.758). However, I will argue below that such effects should not necessarily be classified as illusory, if the observer judgments of 'direct' and 'averted' gaze directions are understood in the observer-related sense rather than the looker-related sense.

Another intriguing gaze perception phenomenon is known as the Mona Lisa effect (Bruce & Young, 1998). It involves the fact that a portrait that appears to gaze at an observer will generally continue to do so when the observer moves about and views the image from different angles (Fig. 2). This is the case although observer motion induces relative rotation of the picture with respect to the observer. Note that if a real 3-D head with fixed iris eccentricity (as in demonstration 3) were to be similarly rotated, its gaze direction would not continue to be aimed at the observer but would change in proportion to the rotation angle. Although today associated by name with Leonardo's famous painting, the effect is in fact one of the oldest reported perceptual phenomena, having been described by the astronomer and geographer Claudius Ptolemy in the 2nd century AD (Lejeune, 1989; Smith, 1996). In the 15th century the theologian and philosopher Nicolaus Cusanus was so impressed with such images that he called them 'icons of God' because, godlike, they look at everybody at the same time (von Kues, 2002). These days this effect may be more readily appreciated by observing faces on billboards: if such a face happens to appear to look at you, you may walk for many tens of meters in any direction while being steadily 'followed' by its gaze. Empirical studies of the effect were carried out by Maruyama, Endo, and Sakurai (1985), Goldstein (1987), and Rogers, Lunsford, Strother, and Kubovy (2003).

A phenomenon that appears not to have been described in the literature previously is the Mirror gaze effect, depicted in Fig. 3. It involves a portrait that gazes at the observer, which is reflected in a mirror. As the reader may verify by setting up such an arrangement, the mirror image of such a portrait will also gaze at the observer. This outcome involves an apparent paradox, for the following reason: if gaze direction were embodied by a real physical object, say a straight wire running between the portrait's bridge of the nose and the observer's bridge of the nose, then the mirror image of the wire would run between the bridge of the nose of the mirror image of the portrait and the bridge of the nose of the mirror image of the observer. Thus if perceived gaze direction would behave like an ordinary physical direction, then the gaze of the mirror image of the portrait would be directed at the mirror image of the observer. However, the gaze of the mirror image is in fact pointed at the real observer, as if engaged in a

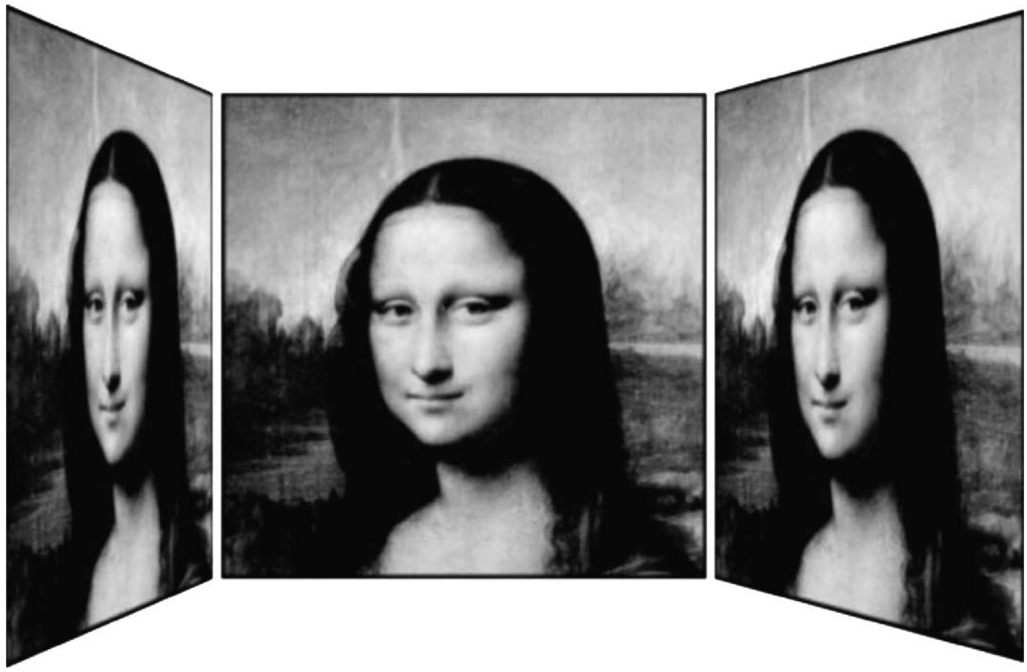

Fig. 2. The Mona Lisa effect: perceived gaze direction of a portrait remains aimed at the observer despite changes of viewing angle. This demonstration, depicting views of differently slanted copies of the picture from the same vantage point, is a variation of the traditional form of the effect, which involves observing the same picture from different vantage points.

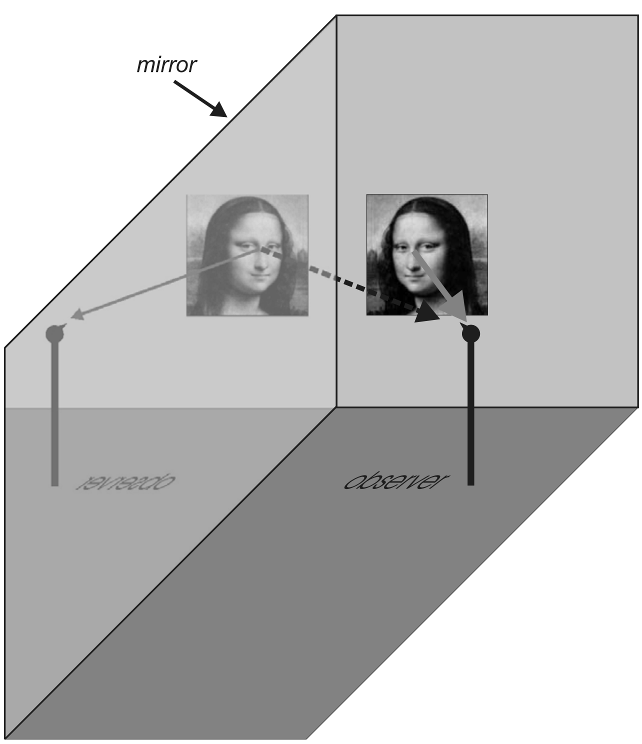


Fig. 3. The Mirror gaze effect: perceived gaze direction of a portrait is not reversed in the mirror! Thick arrow: representation of the perceived gaze direction of the portrait, aimed at the observer. Thin arrow: optical mirror image of the portrait's gaze direction, aimed at the mirror image of the observer. Dashed arrow: actually perceived gaze direction of the mirror image of the portrait. Note that the gaze direction of the mirror image is not equal to the mirror image of the gaze direction.

seemingly improper cross talk between the real world and the mirror world, violating laws of optical reflection. Note that this somewhat puzzling outcome is not based on some peculiarities of mirror images of directions in general. Imagine a situation in which a statue points its arm at you; the direction of pointing could be embodied by a wire running from the finger of the statue to your head. Then not only would the mirror image of the wire run between the mirror image of the statue and the mirror image of your head, but you would also *see* the arm of the mirror image of the statue properly pointing in the direction of your mirror image, rather than at you. Thus in this case the direction set by a real object does reverse in the mirror, in expected conformity with optical laws.

### 1.6. Explaining the Wollaston effect

Why do the portraits in Figs. 1a and c, which have the same iris eccentricities, appear to look in different directions? Commenting on the results of their study of the Wollaston effect, Langton et al. (2004) wrote that 'it seems that head orientation produces a towing effect on the perceived direction of gaze, so that it falls somewhere between *the true line of regard of the eyes* and the angle of rotation of the head' (my italics, p. 757). This claim closely agrees with the conclusions reached by Maruyama and Endo (1983), who obtained similar effects with schematic head cartoons. Such and related interpretations seem to imply that iris eccentricity has dominant importance in the correct determination of the looker's 'true line of regard', whereas head orientation cues induce illusory distortions by 'towing' or biasing judgments away from the true gaze direction. Although the notion that cues of both eye turn and head orientation are needed for accurate judgments of gaze direction was affirmed by Langton et al. (2004), it appears not to have been explicitly applied in the explanation of the Wollaston effect. However, this approach provides a rather straightforward account of the phenomenon: the two portraits in Figs. 1a and c have the same eyes but their heads are turned differently, and that is why they are seen to gaze in different directions. Expressed more formally, the two heads have equal looker-related gaze directions ($\lambda$), but different observer-related head orientations ($\kappa$), and therefore they must have different observer-related gaze directions ($\gamma$), since $\gamma = \kappa + \lambda$. According to this account, the Wollaston effect is not a curious perceptual illusion,but rather provides evidence that our face perception mechanisms are working properly, at least to first approximation, by taking into account the geometrical relations between relevant angles.

Note that a residual sense of being or not being looked at remains even for stimuli consisting of isolated eye pairs (Gibson & Pick, 1963; Langton et al., 2004). For these stimuli, perceived gaze direction is similar to the situation in which such eye pairs are embedded in frontally oriented heads, but the observer's judgments are more variable. My hypothesis is that in such cases the gaze detection mechanisms, lacking any information about the angle of head orientation and the relative placement of the looker's eyes with respect to the head outline, default to the canonical case of the frontal orientation of the head and the symmetrical placement of eyes.

### *1.7. Explaining the Mirror gaze effect*

Why does the reflection in the mirror of a portrait that looks at an observer also look at the observer? Note that one can get rid of the actual mirror and simply use a printed version of the mirror image instead to obtain the same perceptual effect. The mirror-less version of the Mirror gaze effect loses the appeal of the apparent physical paradox involved in the original formulation, but it still poses a legitimate question about gaze perception. As noted above, 'gazing at me' can be expressed by the geometrical condition $\kappa + \lambda = 0$, and the impression that the looker looks at the observer is plausibly based on a counter-balance of eye turn cues and head turn cues. The effect of the mirroring of a portrait is that both the head and the eye turn information are spatially inverted. Thus if the view of the head in the original image indicated that its orientation was $x$ degrees leftwards with respect to the observer, the view of the mirror image will likely convey that it is oriented $x$ degrees rightwards; the same is true for cues of eye turn. Consequently, if the eye and head turn cues in the original image were in counter-balance, so will be the corresponding cues in the mirror image. Thus if a portrait looks at me, then its mirror image will also likely look approximately at me as well. Furthermore, if a portrait does not look at me, then its mirror image is not likely to look at me either.

### *1.8. Explaining the Mona Lisa effect*

Why should a portrait that appears to look at the observer continue to do so when the observer moves about? To answer this, it is instructive to compare situations involving observations of a real 3-D head and a 2-D portrait, using a common format. This is the purpose of Figs. 4 and 5, which involve two observers, A and B, who view the same lookers from two different positions. The top portions of the figures depict graphic overviews of the two situations, the middle portions present them in schematic top views, and the bottom portions provide corresponding purely geometrical diagrams.

Consider Fig. 4 first. The irises of this famous looker are shifted rightwards (as seen by observers) within the eye opening, his head is posed in a certain orientation, and his gaze is aimed in a particular direction in the environment. The two observers receive two different views of the looker's head involving different projections of its face, and his gaze passes much further towards right from observer A than from observer B. The two situations are analyzed more formally in the two bottom panels, in which the looker and the observers are reduced to points. The common, observer-independent elements in the two diagrams are (a) the looker head axis $h$, which connects the looker $L$ and the point $F$ that the looker is facing, depicting his straight ahead direction, (b) the looker gaze axis g, which connects $L$ and the point $G$ that the looker is gazing at, and (c) the angle $\lambda$, subtended by $h$ and $g$, depicting the looker-related gaze direction as the deviation of the gaze axis from straight ahead. The differences between the two situations arise because of the different positions of the two observers and involve (a) the observer view axis $v$, connecting the looker $L$ and each of the observers, A and B, (b) the angle $\kappa$, subtended by $h$ and $v$, which represents the observer-related head turn of the looker, as the deviation of the looker head axis from the observer view axis and (c) the angle $\gamma$, subtended by $g$ and $v$, representing the observer-related gaze direction of the looker, as the deviation of the looker gaze axis from the observer view axis. These relations express formally how observer-related gaze direction and head orientation depend on the position of the observer with respect to the looker. Note that Eq. (1) ($\gamma = \kappa + \lambda$) holds for both observers.

Consider now Fig. 5. The top portion of the figure depicts the fact that, in contrast to the 3-D head in Fig. 4, the portrait in Fig. 5 presents a similar view to the two observers. As is well known, realistic 2-D pictures, such as this portrait, can successfully convey 3-D scenes. Although they do not exist in the real space, such scenes can be regarded as part of a virtual, pictorial 3-D space conveyed by the images (Koenderink, Van Doorn, Kappers, & Todd, 2004), which may be considered as a kind of continuation of the real space. I will first discuss the

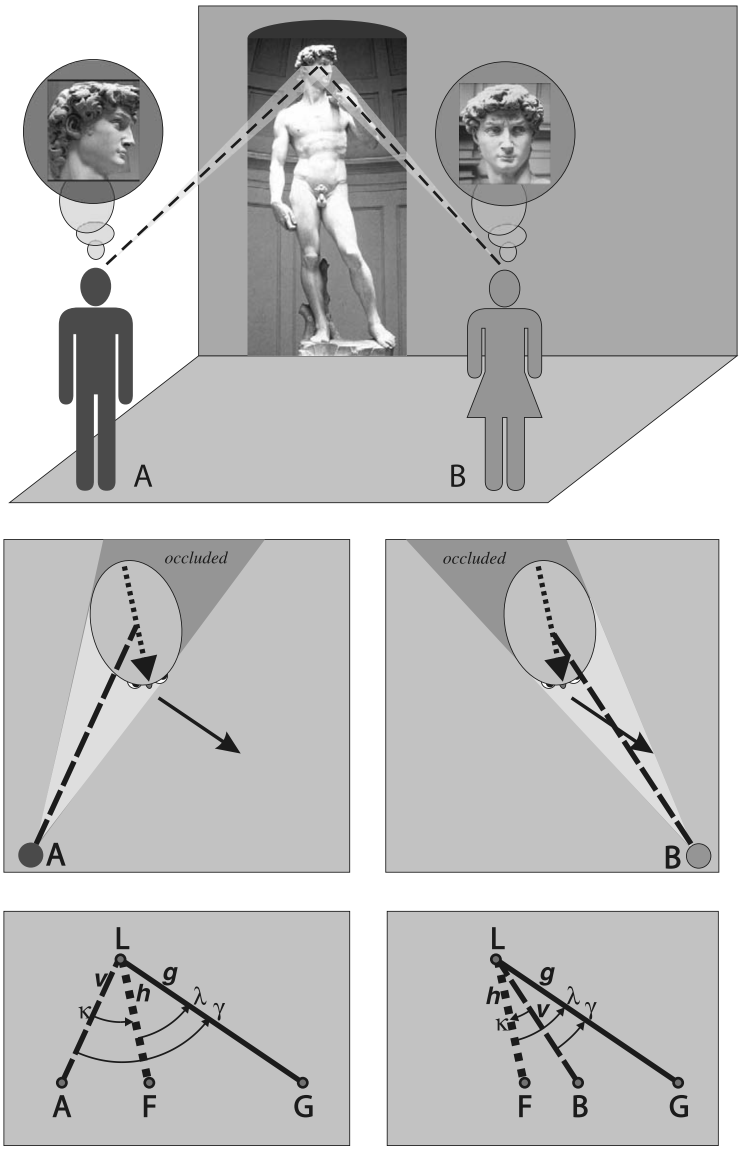


Fig. 4. Observing the gaze of a 3-D head from different positions. The top portion provides a perspective sketch of a situation involving two observers, A and B, viewing a real 3-D statue's head, as well as their different views of the head. The middle portion provides the corresponding schematic top views of this situation, and the bottom portion depicts a purely geometrical representation of the situation. In all portions the observer view axis is represented by the dashed line, labeled as $v$; the looker head axis, defining the pose of the head, is represented by the dotted line $h$; the pose of the eyes is represented by the full line $g$, the looker gaze axis. The head orientation of the looker with respect to the observer corresponds to oriented angle $\kappa$, subtended by $h$ and $v$, looker-related gaze direction corresponds to oriented angle $\lambda$, subtended by $g$ and $h$, and observer-related gaze direction corresponds to oriented angle $\gamma$, subtended by $g$ and $v$. The light and the dark portions of the observer's view cones represent parts of the head and corresponding space which are visible and which are occluded from view, respectively, from the vantage point of the observer.

question of the orientation of the head and then the question of the direction of the gaze of the looker (inhabiting the virtual space) with respect to the observer (inhabiting the real space).

Consider first the case of a symmetrical, face-on portrait. What is the orientation of the looker's head in such a case? The obvious answer is that it is frontal, that is, that the head directly faces the observer. The important point is that this conclusion is valid for most any vantage point: whether the observer stands directly in front of the portrait, or looks at it from the side, the virtual 3-D head must always be oriented towards the observer in order to always present the same, face-on 2-D view (see Anstis et al., 1969; Koenderink et al., 2004; Wallach, 1976, 1985). Although for different observer positions the projection of the picture would be foreshortened, the projection would generally still remain symmetrical and thus would convey a frontally oriented head; asymmetry could only be generated for very slanted viewing angles coupled with near observation distances. Note that constant orientation of the looker's head with respect to the *observer* implies that with respect to the *environment* (which includes not only the real space containing the observer and the picture, but also the virtual space conveyed by the image), the orientation of

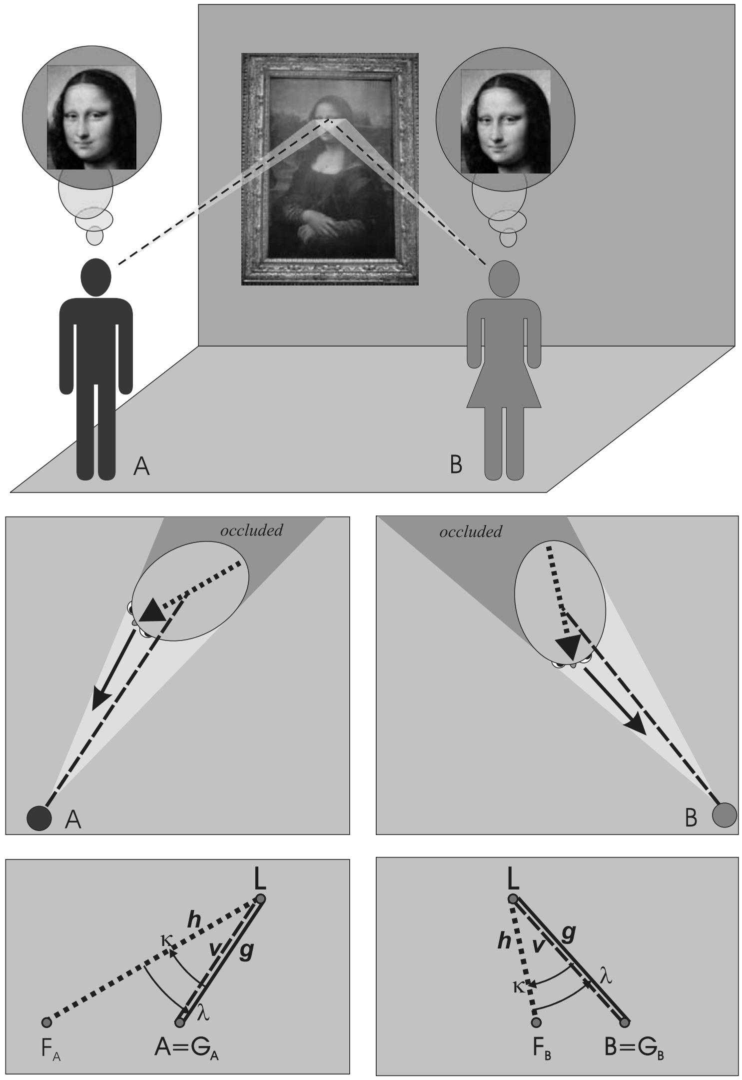


Fig. 5. Observing the gaze of a 2-D portrait from different positions. The three portions of the figure and the various graphical elements have the same features and meanings as described in Fig. 4. See text for details.

the looker's head would have to be *different* for different positions of the observer.

Suppose now that the portrait in question is not symmetrical but presents a view of the head somewhat from the side, as in the case of Mona Lisa. What is the orientation of the corresponding virtual 3-D head with respect to the observer? When a picture of a real head is generated by an artist or a camera, then any particular non-frontal slant of the head with respect to the canvas or film plane corresponds to a particular asymmetrical configuration of the projected view of the resulting portrait, with one side of the face being larger in projection than the other side. Conversely, and this is the important point here, any particular configuration of the facial features in the portrait would provide the observer with cues for the corresponding angle of the slant of the virtual head in pictorial space. As in the symmetrical case, for different observer positions the portrait would undergo various extents of foreshortening, as is visible in Fig. 2; however, for most vantage points the projection of the head would display a similar type of facial asymmetry, conveying a similar slant angle with respect to the observer. For example, if the head is depicted as oriented somewhat leftwards as seen by the observer (as in Fig. 5), then for most vantage points the picture will convey a head with a similar leftward orientation with respect to the observer. Furthermore, as in the frontal case, the orientation of the virtual head in the real + virtual environment would be correspondingly different for different observer vantage points, because the head would need to be oriented differently in order to present the same slanted view to observers. Such a situation is depicted schematically in the middle panels in Fig. 5. The virtual 3-D heads corresponding to the portrait are depicted such that they present the same projected view to both observers; note that the portion of the virtual head that is visible and the portion that is self-occluded is the same in both panels. However, since the two observers occupy different positions in real space, the orientations of the looker's heads in the virtual spaces of the two observers are different. This difference is expressed in the bottom panels by the differences, for observer A and observer B, of the orientations of the looker head axes and the environmental spots ($F_A$ and $F_B$) the looker's heads are facing. However, note that the angle $\kappa$, subtended by the observer view axis $v$ and the looker head axis $h$, is the same for both observers.

Finally, consider the issue of the gaze direction of the portrait. As noted above, the observer-related head orientation $\kappa$ is the same for both observers (say 30° clockwise with respect to the observer view axis $v$). Furthermore, the looker-related gaze direction $\lambda$, which is indicated by the looker's iris eccentricity, is also the same, as seen by both observers. According to Eq. (1), it follows that the observer-related gaze direction $\gamma$ is the same as well. What is that direction? If $\lambda$ has equal absolute value but opposite sign from $\kappa$ (say 30° counter-clockwise with respect to the looker head axis $h$), then, according to Eq. (2), the gaze will be aimed at the observer. This situation is represented in the two bottom panels, in which the observer view axis $v$ and the looker gaze axis g coincide for both observers, making $\gamma = 0$. This constellation of angles is the geometrical basis of the Mona Lisa effect. Given that the impression that the looker 'looks at me' is based on a counter-balance of head and eye orientation cues, as in the Gibson and Pick (1963) proposal, then a 2-D looker that appears to look at me from one position will appear to look at me from most any position, because the head and eyes cues will be in the same counterbalance. Furthermore, if the looker's gaze misses me from one vantage point by a particular angle, specified by a particular combination of head and eyes cues, then it will miss me from most any vantage point by a similar angle. In essence, the explanation of the Mona Lisa effect is that (a) from any viewing position the portrait conveys the same orientation of the looker's head with respect to the observer, and (b) it also always provides the same information about the orientation of the looker's eyes with respect to the head (given by iris eccentricity), therefore (c) it must always signal the same gaze direction of the looker with respect to the observer, because gaze direction is jointly specified by head orientation and eye orientation.

The salient differences between the situations in Figs. 4 and 5 are as follows. A real static 3-D looker has fixed environmental head orientation and gaze direction; these features, obviously, do not change when the observer moves about. What the observer is able to vary, however, is the orientation of the looker's head and the direction of its gaze with respect to him/herself, for example by changing location in order to view the head face-on, oblique, or in profile, or to meet or avoid the looker's gaze; in other words, environment-related features are fixed but observer-related features are variable. In contrast, for a 2-D portrait it is the other way around: when the observer moves, the orientation of the virtual head and its angle of gaze remain generally fixed with respect to the observer, but they change with respect to the environment. One reason why the Mona Lisa effect has a bizarre (or awe-inspiring, in the case of Cusanus) feel to it, is probably because such consequences of one's own motions are so different from what happens when we observe lookers in real space.

That the virtual 3-D head of a 2-D portrait should appear to turn such as to 'follow' the moving observer is not only a geometrical deduction but also a perceptual fact (Anstis et al., 1969; Kubovy, 1986; Wallach, 1976, 1985). However, the stress in previous discussions of this phenomenon was generally put on the dynamic aspect of the effect, that is, that as the observer *moves*, the depicted head appears to *turn* concomitantly. This effect has been explained through an unconscious, reasoning-like perceptual process: the observer moves, notices that there is essentially no change in the observed image, and concludes that this could only have happened if the depicted head had turned in concert with her/his motion, such that it continued to project the same view. Note that this theory fails to predict the actual perceived orientation of the looker's head for any position of the observer, including the initial one before the observer starts to move, and only claims that it will change with observer motion. In contrast, in the above analysis of the Mona Lisa effect motion of the observer is not involved in any essential way, and the perceived orientation of the looker's head is assumed to be based on the asymmetry of the configuration of the relevant projected facial features of the portrait; nevertheless, this static account trivially predicts the salient dynamic fact, that should the observer start to move, the virtual head would appear to turn, because different spatial locations of the observer would correspond to different environment-related orientations of the virtual head.

The Mona Lisa effect is not an isolated curiosity but an instance of a more general perceptual phenomenon: there exist formally similar picture perception effects, but which do not involve gaze direction of portraits. For example, extended arms, guns, passage ways, etc. in some pictures are perceived to be aimed at the observer from any vantage point (see Goldstein, 1979; Kubovy, 1986; Koenderink et al., 2004; Todorović, 2005). The common feature in this class of effects is the dependence of perceived orientation of depicted objects on the position of the observer, probably based on the fact that their 2-D images present the same view from different vantage points, implying different orientations in 3-D virtual pictorial space. In this sense all phenomena in this class may be said to have a common origin. However, this does not mean that identical underlying perceptual mechanisms must necessarily be at work for different classes of depicted objects; thus cues for virtual 3-D orientation for, say, heads and architectural elements, may be based on different types of 2-D stimulus features. For example, there are several candidate stimulus cues of head orientation, such as the (a)symmetry of the shape of the outline of the head, the orientation of the projection of the nose, or the relative placement of inner facial features with respect to the outline of the head (Langton et al., 2004; Maruyama & Endo, 1983; Todorović, 2004;

Wilson et al., 2000). Cues of eye turn include not only the geometrical factor of iris eccentricity but also the photometrical factor of scleral luminance (Ando, 2002). On the other hand, landscape scenes containing objects with extended planar surfaces and straight edges contain different kinds of information, including various salient linear perspective cues, such as vanishing points and horizon ratios. Geometrical analyses indicate that lateral displacements of the vantage point should induce oppositely directed shears of objects in virtual scenes, whereas orthogonal displacements should induce their compression/dilatation (Cutting, 1993; Doesschate, 1964; Gournerie, 1859; Kubovy, 1986; Sedgwick, 1993; Todorović, 2005). The exact interplay of various cues in the determination of perceived orientation in pictorial space remains to be established.

## 2. Experiment

In the preceding considerations I have argued that perception of gaze direction is based on cues of iris eccentricity and head turn. Although studies of gaze direction have varied the looker's head turn, iris eccentricity was not directly manipulated as an independent variable in studies with 3-D lookers. Rather, what was varied instead was the spatial location of the target of the looker's gaze (Cline, 1967; Anstis et al., 1969; Gibson & Pick, 1963; Masame, 1990). Specifying gaze location and head turn of lookers as independent variables does constrain their iris eccentricity as well, but such a design precludes easy evaluation of the specific effect of iris eccentricity on perceived gaze direction. Iris eccentricity is more easily directly manipulated in schematic faces (Maruyama & Endo, 1983; Todorović, 2004), software-manipulated photographs (Langton et al., 2004), and computer-modeled bodies (Seyama & Nagayama, 2005). The latter approach was used here to construct a set of images of heads with quantitatively controlled iris eccentricities and head orientations, and collect judgments on both these two attributes as well as on gaze direction.

### 2.1. Methods

#### 2.1.1. Subjects

Three groups of 11 first-year psychology students from the University of Belgrade took part in the experiments for partial course credit.

#### 2.1.2. Stimuli and design

Two examples of computer-generated portraits are presented in Fig. 6. The software enabled independent control of the model's eyes and head orientation. However, the software-provided angular measures of eye orientation were not relied upon for stimulus specification, since the exact manner of their determination was not available in the manual, and nominally equal angular values involved somewhat different iris positions in the two eyes. Instead, with the head in the frontal position, initially three rightwards (as seen by the observer) iris eccentricities were generated, such that they were approximately equal in both eyes. The distances of the pupil centers from the centers of the eye openings were chosen to amount to 5%, 15%, and 25%, respectively, of the half-width of the eye openings; these distances were measured at the pixel level as precisely as possible, given the resolution of the images and the complex structure of the stimuli. The three eye pairs were excised from the heads, such that the excised regions encompassed the eye openings as well as narrow elliptical surrounding regions. Through left–right inversion, corresponding leftwards eccentricities were produced, so that the full set of iris eccentricities spanned the range from −25% to 25% of eye half-width, in 10% increments. Next, four model heads were generated whose software-provided angles of head orientation were −9.7°, −2.9°, 2.9°, and 9.7°, negative values corresponding to heads oriented towards left, as seen by the observer. These head orientations will be specified here in an analogous manner as iris eccentricities, using image-based measurements rather than relying on software-provided nominal values. These measurements, labeled 'face eccentricities', involved the horizontal position of the center of the bridge of the nose. They were chosen to amount to −24%, −8%, 8%, and 24% of the half-width of the head (thus involving 16% increments), as measured from the center of the head outline at the level of the bridge of the nose. Finally, the excised eyes from the frontal heads were superimposed upon the eye regions of each of the four angled heads, generating 24 portraits. The eyes blended well with the new heads, and no borders were visible under presentation conditions. The shapes of the eye openings of the original eyes from angled heads and the superimposed eyes from frontal heads were not quite the same, because the latter eye openings were symmetrical about the vertical mid-axis whereas the former were somewhat asymmetrical. The horizontal extents of the original and superimposed eyes were not completely identical either. However, the differences were negligible, except for the further eye in the two more extremely angled heads, which was slightly foreshortened. In these cases the excised eyes were compressed horizontally by 2% to fit the widths of the original eyes, a manipulation which did not change their iris eccentricity.

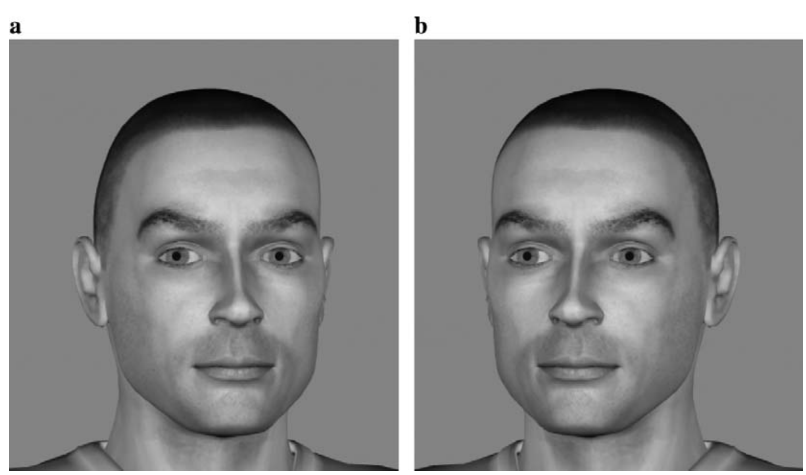


Fig. 6. Examples of synthetic portraits used in the experiment. The images were produced with the program Poser 5 from Curious Labs, a professional body modeling software, used in previous gaze direction research (Seyama & Nagayama, 2005). To generate the portraits, a default male head with neutral expression was used, illuminated from left and right by two symmetrically positioned simulated achromatic light sources; some highlights in the eye regions were edited out subsequently. Note that, similar to Figs. 1a and c, the two portraits have the same iris eccentricity (−15%) but different head turns (+24% and −24%, respectively), and appear to gaze in different directions. See text for details..

*2.1.3. Task and procedure*

The stimuli were presented on a computer screen under control of Superlab Pro 2 software. A head rest was used such that the eyes of the portraits were approximately at the eye height of the observers, and the observation distance was 70 cm. The width × height screen dimensions of the portraits were 140 × 155 mm. The eye openings were 15 mm wide and the head outlines 80 mm wide, on average. Each portrait was repeated 7 times, for a total of 168 stimuli, presented in random order. Additionally, each stimulus was presented once in a practice session immediately preceding the experimental session. The subjects were allotted 3 s to inspect each stimulus, and very rarely failed to respond within this time. After the presentation the screen was blank for 500 ms. Each of the three subject groups had a different task. The subjects in the 'head' group were asked to press the left mouse button if the head of the presented portrait was turned towards their left, and to press the right mouse button if it was turned towards their right. The subjects in the 'iris' group were asked to press the left button if the irises in the portrait were located to the left of the center of the eye opening, and to press the right button if they were located towards the right of the center. The subjects in the 'gaze' group were asked to press the left button if the portrait appeared to gaze at them, and to press the right button if it did not. It was explained to subjects that 'gazing at them' means that the portrait appears to look in the direction of their face, within the region between their ears.

## 3. Results and discussion

In all analyses the dependent variable was the number of times that the left or right mouse button was pressed, for each of the 24 combinations of iris and face eccentricity. A separate two-way completely repeated analysis of variance was performed for each of the three subject groups, with the factors 'face eccentricity' (4 levels) and 'iris eccentricity' (6 levels). For some conditions all subjects in the group answered unanimously (meaning that all response frequencies were equal to 0 or to 7), so that the corresponding cells in the analysis involved no variance, causing computational problems; these problems were solved by adding 0.001 to the response of a single subject in each such condition.

Fig. 7 presents the results of the 'head' group for the 'head is turned rightwards' response. As expected, as the portrait's head turned from left to right, the mean percentage of 'rightwards' responses increased. Discrimination was practically perfect for the two absolutely larger face eccentricities (−24% and +24%), but the subjects were less unanimous for the two middle, absolutely smaller face eccentricities (−8% and 8%). In addition, for these two face eccentricities there was a tendency for the response frequencies to increase somewhat with increasing iris eccentricity. In the ANOVA, face eccentricity was significant, with $F(3,30) = 243.39$, $p < 0.00001$, as was iris eccentricity, with $F(5,50) = 3.10$, $p < 0.017$, and their interaction was not significant, $F(15,150) = 1.36$, $p > 0.17$. To test the origin of the iris eccentricity effect, the two middle face eccentricities were removed from the analysis. In this post hoc ANOVA the effect of iris eccentricity disappeared, $F(5,50) = 1.60$, $p > 0.17$, whereas face eccentricity was highly significant, $F(1,10) = 40178.34$, $p < 0.00001$, and the interaction was not significant, $F(5,50) = 0.72$, $p > 0.6$.

Fig. 8 presents the results of the 'iris' group for the 'irises are located rightwards from center' response. As the position of the iris shifted from left to right, the frequency of 'rightwards' responses increased, displaying the classical psychometric sigmoidal shape. This trend was common for all four levels of face eccentricity, but the sigmoids for different levels did not quite overlap; for the two middle, absolutely smallest iris eccentricity levels (+5% and −5), the frequency of 'rightwards' responses tended to decrease with increasing face eccentricity. In the ANOVA, face eccentricity was significant, with $F(3,30) = 8.26$, $p < 0.0004$, as was iris eccentricity, with $F(5,50) = 310.87$, $p < 0.00001$, and their interaction was significant as well, $F(15,150) = 4.22$, $p < 0.00001$. To test the origin of the face eccentricity effect the middle two iris eccentricities were removed from the analysis. In the post hoc ANOVA face eccentricity became insignificant, $F(3,30) = 1.77$, $p > 0.17$, whereas iris eccentricity was highly significant, $F(3,30) = 2051.41$, $p < 0.00001$, and the interaction missed the conventional significance criterion, $F(9,90) = 1.97$, $p > 0.05$.

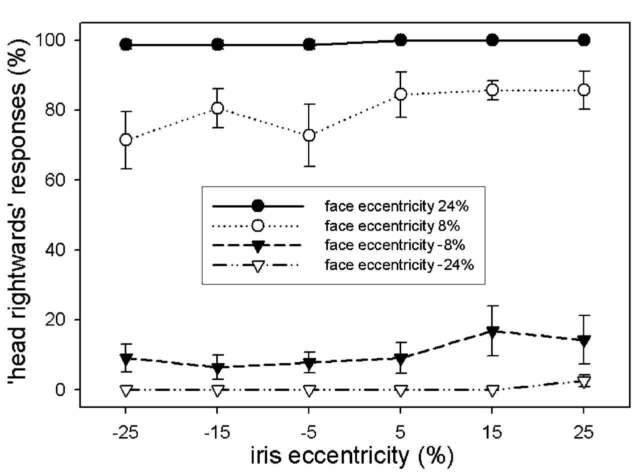


Fig. 7. The effects of iris eccentricity and face eccentricity on the percentage of judgments that the portrait's head is turned rightwards. Bars depict standard errors.

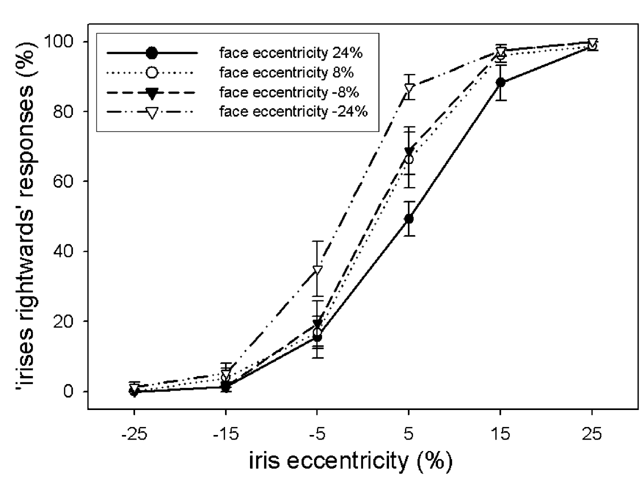


Fig. 8. The effects of iris eccentricity and face eccentricity on the percentage of judgments that the portrait's irises are located to the right of the center of the eye opening. Bars depict standard errors.

Fig. 9 presents the results of the 'gaze' group for the 'portrait gazes at me' response. As the position of the iris shifted from left to right, for all four face eccentricities the frequency of the 'gazes at me' response first increased and then decreased. However, the peak of the response distribution differed for different face eccentricities, shifting leftwards as face eccentricity increased from −24% to 24%. In the ANOVA, face eccentricity was significant, with $F(3,30) = 12.92$, $p < 0.00002$, as was iris eccentricity, with $F(5,50) = 82.45$, $p < 0.00001$, and their interaction was significant as well, $F(15,150) = 23.64$, $p < 0.00001$.

The results of the 'head' and 'iris' group showed that the subjects were successful in discriminating levels of face and iris eccentricity (for threshold values see below). However, the responses to the two variables were not quite independent from each other (see Langton, 2000); namely, for the absolutely smallest values of these variables (least different from zero), the response to different levels of one variable were somewhat affected by the values of the other variable. Most relevant in the present context were the results of the 'gaze' group, which showed how levels of iris and head eccentricity interacted to determine perceived gaze direction. Eyes with irises in same locations evoked different gaze direction judgments when combined with differently turned heads. For example, of the two portraits in Fig. 6, the one with face eccentricity equal to 24% was judged to look at observers 85.7% of the time, whereas the one with face eccentricity equal to −24% was judged to look at observers 7.8% of the time.

The results in the gaze task are in general agreement with the findings of Langton et al. (2004), experiment 1A, but their interpretation here is different. The combined data from the three experiments clearly corroborate the notion that cues of iris eccentricity and head orientation interact in a geometrically plausible manner to determine perceived gaze direction. In accord with Gibson and Pick's (1963) proposal, and consistent with Eq. (2), increasingly rightwards shifts of values of one independent variable had to be counterbalanced with increasingly leftwards shifts of values of the other, in order to make the gaze of the portrait appear directed at the observer. More concretely, each consecutive 16% shift of face eccentricity rightwards was accompanied by a corresponding 10% leftwards shift (in units of iris eccentricity) of the peak of the response distribution. The size of this shift could be estimated more precisely when the response distributions for the four face eccentricities were fit with normal curves (for details see below): the average distance between their centers was equal to 5.89% iris eccentricity.

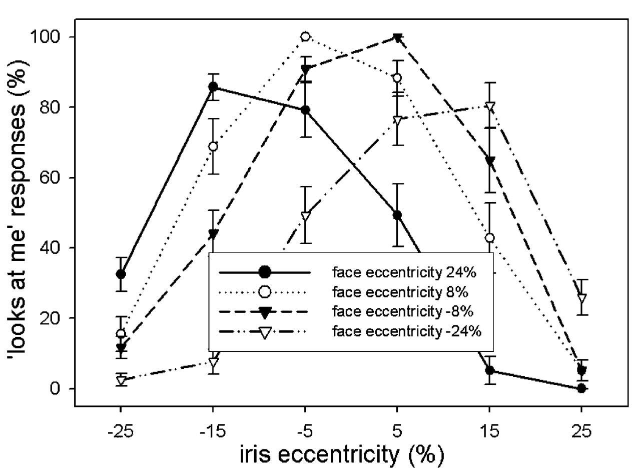


Fig. 9. The effects of iris eccentricity and face eccentricity on the percentage of judgments that the portrait gazes at the observer. Bars depict standard errors.

The obtained data can be used to calculate discrimination thresholds for the studied tasks. For the 'iris' group, the data for the six eccentricities, averaged across the four head orientations, were fit with a sigmoid curve of the form $y = 100/(1 + \exp(-(x - C)/S))$, with the median $C$ and the slope $S$ as free parameters. The $R^2$ of the fit was larger than 0.99. The slope parameter $S$ can be converted into semi-interquartile range, a measure of threshold, which amounted to 5.33% in iris eccentricity units. This value corresponds to a visual angle shift of the iris of 2 min of arc. This magnitude lies somewhat outside of the 0.3–1.1 min of arc range of gaze direction discrimination thresholds obtained with frontal and angled head orientations of live lookers, calculated from data of Gibson and Pick (1963) and Cline (1967). Analogous procedures were applied to calculate thresholds for the 'head' group data. The $R^2$ of the fit of the sigmoid was again larger than 0.99, and the semi-interquartile range amounted to 4.99% in face eccentricity units. When the four head orientations were re-expressed in terms of software-provided angular measures, the semi-interquartile range amounted to 1.81° of head turn angle. This threshold value is close to the 1.9° value reported by Wilson et al. (2000) for discrimination of head turns from the frontal orientation; the stimuli in that study were filtered photographs of real heads. To obtain threshold measures for the 'gaze' group, the four response distributions were first fit by normal curves. All $R^2$'s of the fits were larger than 0.97. The obtained four standard deviations were transformed into semi-interquartile ranges; these values ranged between 7.76% and 8.46% in iris eccentricity units, with a mean of 8.06%.

The fact that in the present study the mean discrimination threshold for gaze direction (8.06%) was larger than for iris location (5.33% in same units) is consistent with the idea that gaze judgments were, in part, based on judgments of iris eccentricity. However, there are two important caveats. First, the gaze discrimination threshold might have been smaller if a stricter criterion of 'gazes at me' responses had been used, such as 'portrait looks at the bridge of my nose'; however, such a criterion might not correspond to the ordinary sense of being looked at. On the other hand, if looking at either of my two eyes should count as 'gazing at me', then such judgments would necessarily involve some spatial breadth. Second, the theoretical relevance of actual values of thresholds depends on the details of the mechanisms for gaze discrimination, of which little is currently known. One possible mechanism, which may be labeled as 'analytical', is that the visual system first independently extracts iris eccentricity and head orientation information from the looker's head, and then combines these two measures to form the gaze direction judgment; in this case one would indeed expect the gaze threshold to be larger than the iris threshold, because it would also be affected by the head threshold. However, another possibility, which may be labeled as 'holistic', is that gaze detection mechanisms involve specialized processing geared for extracting the relevant information directly from the whole facial configuration. In this case the values of thresholds of independent assessments of iris eccentricity and head turn would not necessarily predict the value of the threshold of perceived gaze direction in any simple way. For example, a direct mechanism might involve a bank of facial templates, each tuned, more or less broadly, to detect a pattern involving a particular constellation of iris eccentricity and head turn; each such template would be associated with a particular gaze direction, and the one currently most activated would signal the gaze of the present looker. Such a mechanism would respond to whole spatial configurations and would at no stage involve separate measurements of iris location and head turn, which would need to be integrated subsequently. Detecting gaze direction (and in particular detecting observer-aimed gazes), is probably biologically much more relevant than detecting iris and head turns by themselves, and thus might warrant specialized neural machinery. However, as demonstrated in the present study, sensitive independent registration of a looker's iris eccentricity and head orientation is certainly also possible. Whatever the underlying mechanism, a portion of the extensive physiological basis of face perception, located in the fusiform gyrus, superior temporal sulcus and other brain areas, is probably dedicated to gaze detection (Hoffman & Haxby, 2000).

Finally, note that both the analytical and the holistic mechanism, as described above, may be classified as 'configural', because they both feed on information gathered over a larger region of the face, though in different ways. This is in contrast to truly local mechanisms, which would rely only on some circumscribed facial feature. This feature does not necessarily have to be iris eccentricity. For example, registration of gaze direction might conceivably be based on the detection of the direction of the surface normal of the cornea at the center of the pupil. Instead of gaze direction being detected indirectly (eye turn relative to head *plus* head turn relative to observer, as argued for in this paper), it would be detected directly (eye turn relative to observer). Such a mechanism could in principle dispense with both iris eccentricity and head turn information, similarly to some procedures used in technical gaze tracking devices. It would remain to be established, however, how such an approach would account for effects of head orientation on gaze perception, and in particular why the same eyes embedded in different heads can be perceived to gaze in different directions.

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