ABSOLUTE AND RELATIVE VISUAL DIRECTION OF MONOCULAR AND BINOCULAR TARGETS

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Abstract

Seven experiments designed to measure the accuracy and precision of absolute and relative direction judgments under monocular and binocular viewing conditions are presented. The experiments assess the validity of claims in the literature that (a) the cyclopean eye (the centre from which visual direction judgments are made) is not fixed in the head, but moves along the interocular axis as a function of the stimulus situation and the eye(s) used to view the stimuli, and (b) absolute direction during monocular viewing is based on signals from the viewing eye only. The results of the experiments refute these claims and elucidate which types of visual direction tasks are germane to specifying the location of the cyclopean eye. Specifically, the results show that monocular relative direction judgments are highly accurate and precise, are independent of binocular eye position, and cannot be used as the basis from which to infer the position of the cyclopean eye. Absolute direction judgments, on the other hand, are less precise than relative direction judgments, and the accuracy of both monocular and binocular absolute direction judgments is dependent upon binocular eye position. When the eyes converge accurately on the target of interest, absolute direction judgments are accurate. When the eyes converge inaccurately on the target of interest, which is often the case during monocular fixation, absolute direction judgments are inaccurate. These results clarify the important distinction between relative and absolute visual direction and are discussed in terms of how visual directions specified from the cyclopean eye (perceptual variables) are derived from the inputs from the two eyes (physical variables).

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Chapter One: General Introduction*

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To interact with objects in the environment we need accurate and precise information about the locations of the objects, both with respect to ourselves (an absolute or egocentric direction task) and with respect to other objects in the visual field (a relative or exocentric direction task). How one makes these judgments about the directions of objects has been of interest to scientists since the time of Ptolemy (ca. 100–175) and Ibn al-Haytham (965–1040, also known by his Latin name of Alhazen). Ptolemy's books II and III of his *Optics* discuss binocular vision and describe where an object appears to be while fixating at a particular point (Howard & Wade, 1996). Alhazen confirmed most of Ptolemy's observations.

Despite this long history, the distinction between absolute and relative direction judgments is often confused. To avoid such confusion, it is important to clearly distinguish between egocentric (absolute) and exocentric (relative) frames of reference.

1.1 Frames of reference

People can judge the direction of an isolated object in any of the following reference frames, the first three of which are egocentric reference frames because they involve some part of the observer's body.

1. Oculocentric frame Oculocentric judgments of direction are with respect to the visual axis or one of the principal retinal meridians.
2. Headcentric frame Headcentric judgments of direction are with respect to the median plane of the head and the mid-transverse plane through the eyes. A headcentric judgment requires the observer to register the position of the images in the eyes (oculocentric component) and the angular position of the eyes in the head (eye-position component). When an observer fixates an object, its images can be expected to fall

precisely on the foveas and there is little uncertainty about the oculocentric direction of the object. In this condition, a headcentric judgment reduces to the task of registering the direction of gaze. An exception to this precision occurs when there is a fixation disparity, which is a slight deviation of the visual axes from the intended point of convergence, when both eyes are open. Fixation disparity magnitudes reported in the literature vary as a function of how they are measured (Kertesz & Lee, 1987; Remole, 1983, 1984, 1985). By definition, however, they are too small to cause diplopia and the different oculocentric components in the two eyes, resulting from fixation disparity, are averaged (Ono, Angus, & Gregor, 1977).

3. <u>Torsocentric frame</u> Torsocentric judgments are made with respect to the median plane of the body and some arbitrary horizontal plane. They must now take account of the position of the head on the torso.

4. <u>Exocentric frame</u> In an exocentric judgment the direction of one visual object is judged with respect to a second object or with respect to an external reference frame. When the reference frame is visual, only the relative locations of retinal images are required.

In order to interpret responses from an experiment on visual direction the experimenter must know which frame of reference observers are using. For example, when asked to set a stimulus to "straight ahead" an observer could set it (1) on the visual axis, (2) on the median plane of the head, (3) on the median plane of the torso, or (4) in the centre of the visual field. The responses would coincide only when object, visual axis, and median planes were aligned.

Oculocentric judgments require only one source of information—image position.

Headcentric judgments require additional information about the position of the eyes in the head. Torsocentric judgments require, in addition, information about the position of the head on the torso. Exocentric judgments require only information about the relative locations of retinal images. One would expect precision to be less when more sources of information are required, since each source of information adds noise.

In the following discussion we concentrate on headcentric directional judgments with some attention to exocentric direction tasks. We will see that the failure to clearly distinguish between egocentric and exocentric frames of reference has produced confusion.

1.2 Headcentric direction and the egocentre

1.2.1. Basic law of visual direction

When a near object is fixated binocularly, the eyes point in different directions with respect to the median plane of the head, and yet the visual object appears to have a single direction in space. Somehow directional information from the two eyes combines to produce a unitary sense of visual direction. One is then confronted with the question of which location in the head serves as the origin for directional judgments. One possibility is that it is the dominant eye, but most evidence suggests that directional judgments are referred to a point midway between the eyes, known as the **cyclopean eye** or **visual egocentre** (Mapp & Ono, 1999; Mapp, Ono, & Barbeito, 2003). Therefore, information from each eye must be transferred to the cyclopean eye. This section is concerned with how this is done, both when the positions of the two images correspond, and when directional information is derived from disparate images.

Analysis of headcentric direction starts with the basic unit of the visual line which is common to directional judgments in all frames of reference. A visual line is any straight line passing through the pupil and the nodal point of an eye (the point in the lens where all visual lines intersect). A visual line is the locus of all points, fixed relative to the eye, which stimulate a given point on the retina. The visual line through the centre of the fovea is the visual axis. Any other visual line may be specified in terms of its angle of azimuth with respect to the eye's median plane, and of its angle of elevation with respect to the eye's mid-transverse plane.

A visual line may also be specified in terms of its angle of eccentricity and meridional angle. For a given position of an eye, each fixed point in space has only one physical direction and only one apparent direction. An exception to this rule is provided by monocular diplopia or polyopia in which single objects appear double or multiple, either because of an optical defect or because of defective neural processing. All points on the same visual line have the same visual direction and appear visually superimposed. Objects on different visual lines of one eye appear in distinct locations, except objects that are closer together than the resolution threshold of the visual system.

The preceding statements are summed up by the basic **law of visual direction,** which states that *all objects on the same visual line are judged to be in the same direction, which is unique to that set of objects*. The law does not specify where the objects in the set appear with respect to any of the four frames of reference. It simply states that the objects appear aligned (superimposed) in each frame of reference.

1.2.2. Laws of headcentric direction

For a given angular position of an eye, points on the same visual line are also judged to be in the same headcentric direction. Thus, the **law of headcentric direction** states that, *for a given position of the eye in the head, objects lying on the same visual line are judged to be in the same headcentric direction with respect to the cyclopean eye, which is unique to that visual line.*

The basic demonstration of this law was reported by Ptolemy (ca. AD 150) (see Howard & Wade, 1996; Tyler, 1997), Alhazen (see Howard, 1996), and Wells (1792). The concept of the cyclopean eye was proposed by Towne (1865, 1866), Hering (1868/1977, 1879/1942), and LeConte (1871, 1881) at approximately the same time (See Ono, Wade, & Lillakas, 2009; Wade et al., 2006).

The cyclopean eye, or visual egocentre, is the location in the head towards which visually aligned objects appear to point. Note that the cyclopean eye is not necessarily the point towards which monocularly aligned objects actually point, which is, of course, the nodal point of the eye. In fact, as we will see later, the cyclopean eye is normally in the median plane of the head.

Next, assume that, in the binocular field, images falling on corresponding points in the two retinas have a common visual direction. Each pair of corresponding points is associated with a pair of corresponding visual lines. It follows from the law of visual direction and the principle of corresponding points that all objects on either of a pair of corresponding visual lines appear spatially superimposed. This is the law of common binocular directions applied to corresponding lines. In itself this does not prove that objects lying along corresponding visual lines will appear to be in the same headcentric direction for the two eyes. For instance, if each eye were a centre of reference for headcentric direction, an object seen by one eye and an object on a corresponding line in the other eye would seem to be in a different direction even though the objects appeared to occupy the same position in space. In fact, corresponding visual lines are referred to the cyclopean eye, which is normally midway between the eyes. These principles can be summed up by the **law of the cyclopean eye**. Points *on any visual line of either eye appear aligned with the cyclopean eye midway between the eyes*. Any line through the egocentre is a cyclopean line. Since the egocentre does not correspond to the nodal point of either eye, cyclopean lines and visual lines do not coincide. The direction of a cyclopean line can be specified with respect to the coordinates of the cyclopean eye or with respect to headcentric coordinates.

To say that a set of points appears aligned with the egocentre does not specify the apparent direction of the points relative to the median plane of the head, since direction relative to the median plane cannot be specified by one point on the median plane. A metric for headcentric direction is provided if the direction of the point of binocular fixation is judged correctly. This is a point on the horopter where the two visual axes intersect. We then generalize this idea and state that the headcentric directions of all points on the horopter (points where corresponding lines intersect) are judged correctly.

Thus, the apparent direction of lines within the horizontal plane of regard may be specified if (1) the directions of points on the horizontal horopter are judged correctly and (2) points lying on the same visual line are perceived as collinear. From the law of common binocular directions and from these assumptions one can derive the **law of cyclopean projection**. This states that *points on any visual line appear to be aligned with the cyclopean eye and the physically defined point where the visual line intersects the horopter*. This can be regarded as a corollary to the law of common binocular directions.

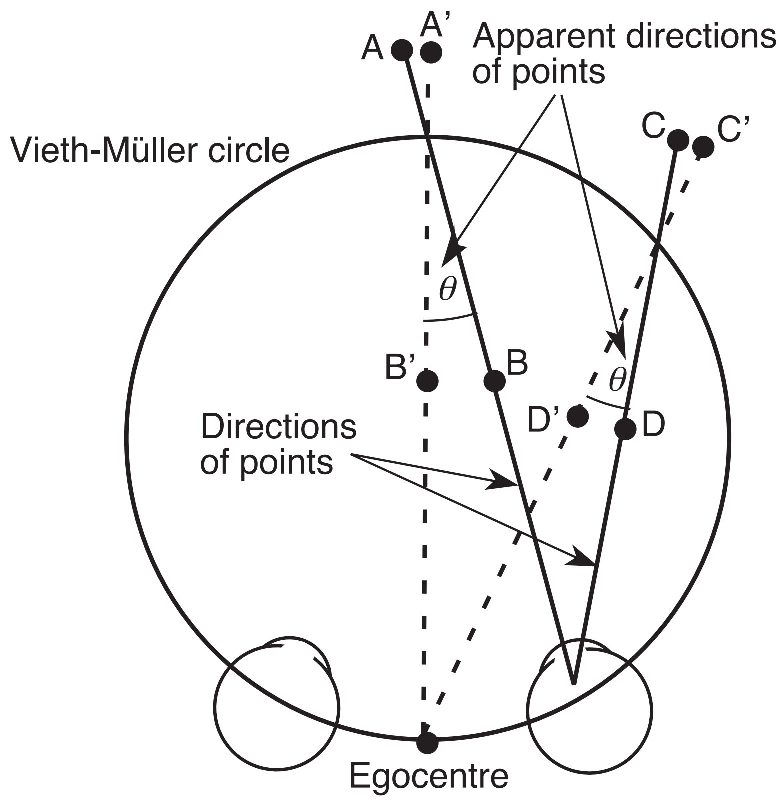

Figure 1.1. The egocentre and perceived direction. Assume that the visual egocentre lies midway between the eyes on the Vieth-Müller circle and that the headcentric directions of points on the horopter are correctly judged. Points, such as *A* and *B*, lying on a visual axis will appear aligned with the egocentre and the point where the visual axis intersects the horopter. The angle θ between the visual axis and the line on which the objects appear is half the vergence angle. Objects, such as *C* and *D*, on another visual line, also appear displaced by angle θ.

With symmetrical convergence, points on the visual axis of either eye appear in the median plane of the head. The angle θ, between the visual axis and the median plane, is half the angle of convergence, as shown in Figure 1.1. Assume that the horopter conforms to the Vieth-Müller circle and that the cyclopean eye lies on this circle, midway between the eyes. Then θ is the angle between any visual line and the cyclopean line on which objects on the visual line appear to lie. Thus, for a given convergence, any visual line will appear displaced by half the vergence angle with respect to that visual line.

The cyclopean line passing through the intersection of the two visual axes is called the **cyclopean axis** or the **common axis**. The **law of differences in headcentric directions** states that *the angle formed by a visual axis and a visual line is seen as the difference in the visual directions between the cyclopean axis and the cyclopean line*. A corollary of this law is that *an angle formed by two visual lines of an eye is seen as the difference in the visual directions at the cyclopean eye*. In Figure 1.1, the angle formed by A and C is equal to the angle formed by A' and C'.

1.2.3. Demonstrations of laws of headcentric direction

Hering stated the law of the cyclopean eye as:

> "*For any given two corresponding lines of direction, or visual lines, there is in visual space a single visual direction line upon which appears everything which actually lies in the pair of visual lines*." (Hering, 1879/1942, p. 41).

The truth of this statement was demonstrated in the following way:

> *"Let the observer stand about half a meter from a window which affords a view of outdoors, hold his head very steady, close the right eye, and direct the left to an object located somewhat to the right. Let us suppose it is a tree, which is well set off from its surroundings. While fixing the tree with the left eye a black mark is made on the windowpane at a spot in line with the tree. Now the left eye is closed, and the right opened and directed at the spot on*

> *the window, and beyond that to some object in line with it, for example, a chimney. Then with both eyes open and directed at the spot, this latter will appear to cover parts of the tree and chimney. Both will be seen simultaneously, now the tree more distinctly, now the chimney, and sometimes both equally well, according to which eye's image is victor in the conflict. One sees therefore, the spot on the pane, the tree and the chimney in the same direction*." (Hering, 1879/1942, p. 38)

Figure 1.2 illustrates this situation.

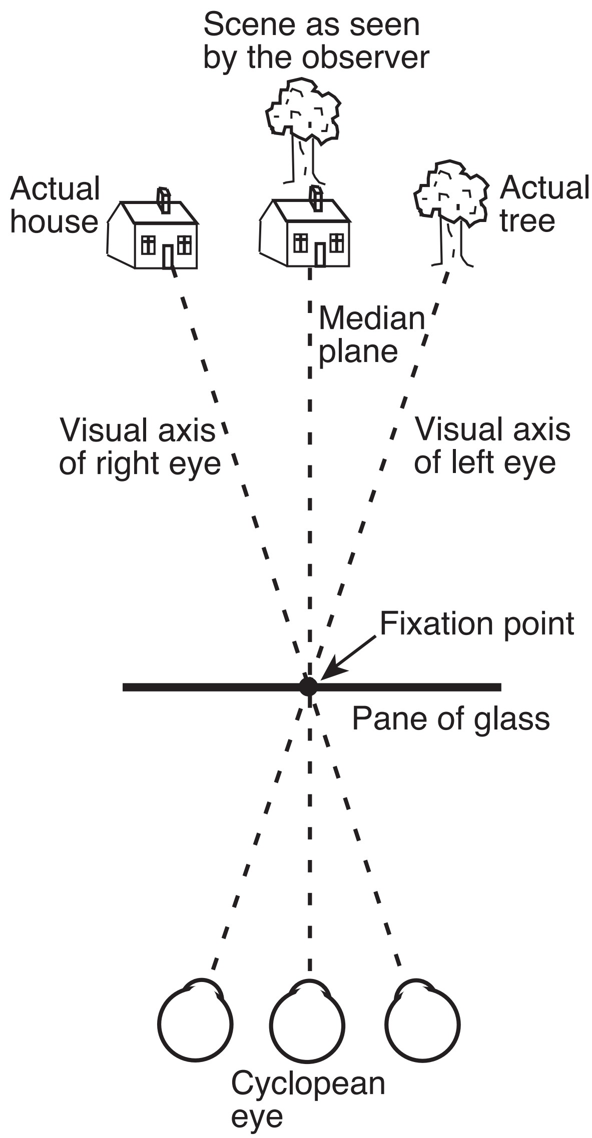

Figure 1.2. Hering's illustration of cyclopean direction. While fixating a distant tree with only the left eye open, a black spot on the pane of glass is aligned with the tree. When both eyes fixate the spot, a distant house in line with the spot for the right eye, and the tree aligned with the left eye, appear superimposed.

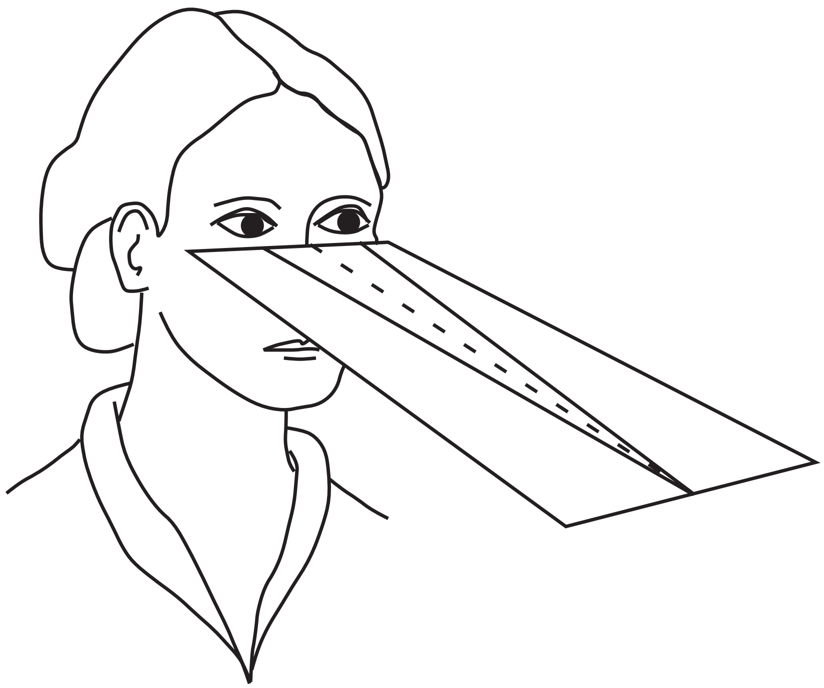

Figure 1.3. Illustration of the egocentre. Demonstration that visual directions are referred to an egocentre. Each line must point to the pupil of an eye, and fixation should be on the point where the lines meet. The two lines appear super-imposed in the median plane of the head.

Another way to illustrate the concept of the cyclopean eye is to draw two lines on a card so that when the card is held in front of the eyes, the lines extend precisely from the centre of each pupil to an apex, as in Figure 1.3. A thin vertical separator down the centre of the card ensures that each eye sees only its own line. If the lines are visually distinct—for instance in different colours—and if fixation is maintained on the point where they intersect, the two lines appear as one line extending from a point between the eyes. Ptolemy used this display in the second century, Alhazen used it in the eleventh century, and Towne used it in the nineteenth century.

We produce a unified sense of direction from the distinct vantage-points of the two eyes by judging directions with reference to the cyclopean eye. The directions of objects on any pair of corresponding visual lines are judged as though the objects are seen by the cyclopean eye, as shown in Figures 1.3 and 1.4.

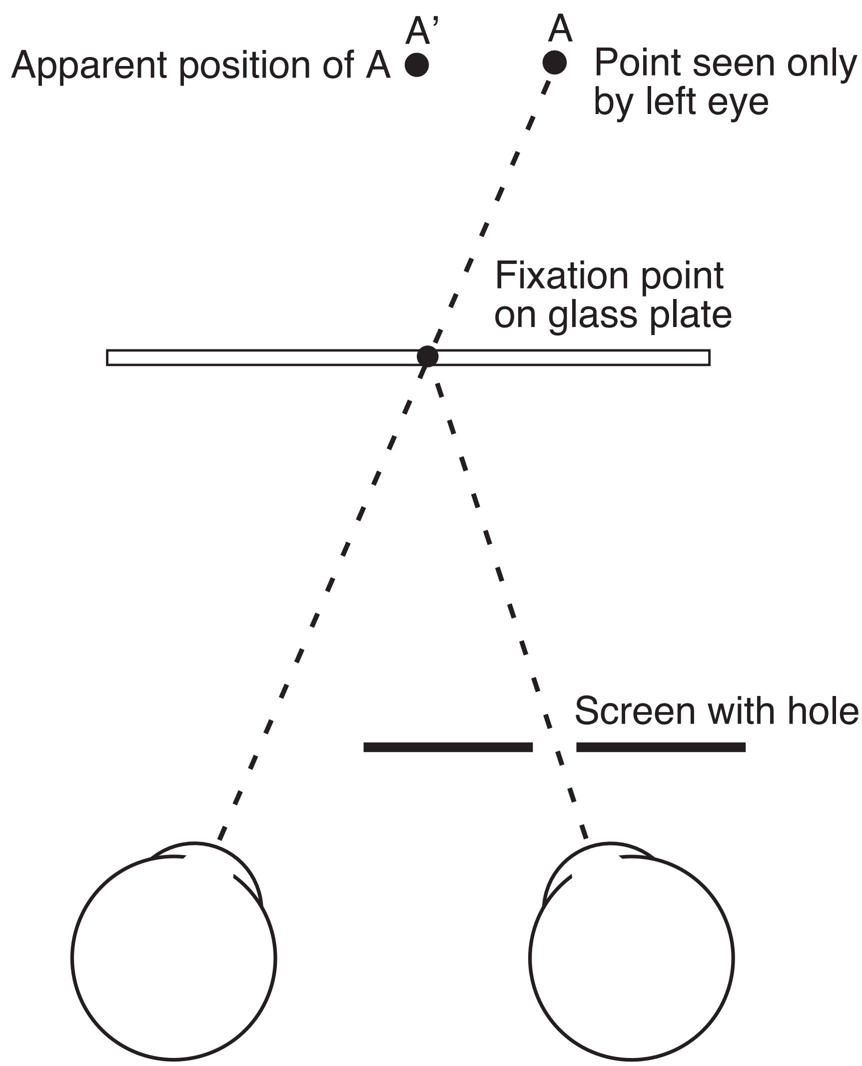

Figure 1.4. Illustrating Hering's law of visual direction. A pinhole in a card is held several centimetres in front of the right eye. A black dot on a pane of glass is fixated directly by the left eye and through the pinhole by the right eye. Object A, on the visual axis of the left eye, appears at A' in the median plane beyond the fixation point, even when the right eye is closed

When 2-year-old children sight an object through a tube, they place the tube midway between the eyes (Church, 1966). This is called the **cyclops effect**. Barbeito (1983) found that about one-third of a group of 3-year-old children behaved this way but only about one in ten of 4-year-olds. The cyclops effect has also been reported in young strabismic children and in children under 4 years of age, two years after they had one eye removed (Dengis, Steinbach, Goltz, & Stager, 1993). Older observers (5.8 to 22.8 years) showed some cyclops effect in visual tasks such as aligning a line or a moving stimulus with a landmark of the head (the bridge of the nose or edge of the pinna) but less so than age-matched binocular observers (González, Steinbach, Gallie, & Ono, 1999). Thus, young children behave as if they see out of the cyclopean eye and they must learn to bring a tube to one or the other eye. That is not to say that they consciously believe that their eyes are in the centre of the head. Even after children have learned to bring a tube to one eye, they must learn to close the other eye (Dengis et al., 1996; Dengis, Steinbach, Ono, & Gunther, 1997). Moreover, if visual feedback is eliminated as the tube is raised toward the face, then adults behave as children do and place the tube midway between the eyes (Dengis, Simpson, Steinbach, & Ono, 1998).

A corollary of the law of the cyclopean eye is that two objects at different distances, that appear aligned when viewed with one eye, will not appear aligned when viewed with the other eye. This follows from the fact that two objects at different depths cannot fall simultaneously on corresponding visual lines in the two eyes, because corresponding visual lines intersect in only one point. When one sights a distant object through a ring with both eyes open, there is conflicting information about the alignment of the ring and the object. In this situation, binocular disparity is too large to allow fusion.

Most people accept the information in one eye—the sighting eye—and ignore what they see with the other eye. The sighting eye is therefore the eye one uses preferentially in making judgments about the alignment of objects well separated in depth. This is not to say that the sighting eye becomes the location in the head that serves as the origin of directional judgments, for it is not.

Points lying on a horizontal line extending away from the observer in the median plane of the head stimulate noncorresponding points in the two retinas, except where the line intersects the horopter. When the line is just below eye level it appears as a cross with its intersection point on the horopter. This cross is easily observed by taking a card with a line drawn on it and holding it just below eye level with one end of the line touching the bridge of the nose. It is as if the space before one eye had rotated scissors-fashion about the fixation point over the space before the other eye. This has the effect of apparently transferring the objects on each visual axis to the median plane and, for each eye, transferring objects in the objective median plane of the head to the visual axis of the opposite eye. Ptolemy and Alhazen described this effect.

With symmetrical convergence, all visible objects imaged on the foveas are judged to have the same headcentric direction, which lies approximately in the median plane of the head. This is true even when only one eye is open or when, because of an obstruction, the object can be seen by only one eye. Hering demonstrated this in the following manner. A card with a pinhole at its centre is held several centimetres in front of the right eye. A black dot, *F,* on a pane of glass is fixated directly by the left eye and by the right eye through the pinhole, as illustrated in Figure 1.4. A small object, *A*, is placed beyond the glass on the visual axis of the left eye. Although *A* is seen by only the left eye and is to the right of the median plane, it appears in the median plane behind the point *F*. If the right eye is closed, the impression remains the same. The apparent position of *A* changes only if the eyes change their positions.

1.2.4. Summary

Here are five laws or principles of visual direction for distinct point-like stimuli:

1. <u>The law of visual direction</u> Objects on a given visual line have the same visual direction and appear aligned, or superimposed in any frame of reference. Objects falling on discriminably different visual lines appear spatially separate in any frame of reference.
2. <u>The law of headcentric direction</u> For an eye in a fixed direction of gaze relative to the head, objects lying on the same visual line are judged to be in the same headcentric direction, which is unique to that visual line.
3. <u>The law of the cyclopean eye</u> In monocular or binocular viewing, all visual lines of either eye appear to point to a common cyclopean eye midway between the eyes.
4. <u>The law of cyclopean projection</u> Points on a visual line appear to lie on the cyclopean line that geometrically intersects the visual line on the horopter. It follows that objects on the visual axes of the two symmetrically converged eyes appear to extend in the median plane of the head from a point midway between the eyes. In general, for asymmetrical stimuli and asymmetrical convergence, objects on any pair of corresponding visual lines appear on a cyclopean line passing through the cyclopean eye and the point in the horopter contained in both visual lines. An object seen and fixated by only one eye is judged to be in the direction of a line that intersects the cyclopean eye and the point of binocular convergence.

5. The law of differences in headcentric directions The angle formed by a visual axis and a visual line is seen as the difference in the visual directions between the cyclopean axis and the cyclopean line.

Ono (1979, 1991) and Ono and Mapp (1995) described a similar set of principles. Although Hering is usually credited with first formulating principles of visual direction, Ptolemy described cyclopean projection in the 2nd century AD and so did Alhazen in the 11th century. Principles of cyclopean projection were also illustrated by William Briggs in 1676 and by Wells in his book *Essay upon Single Vision with Two Eyes*, written in 1792. This was 87 years before Hering wrote his account (Ono, 1981; van de Grind, Erkelens, & Laan, 1995). Moreover, LeConte (1871,1881) independently proposed the laws of visual direction that make the same predictions and suggested the term "the cyclopean eye" for the origin of visual direction (see Wade et al., 2006).

These laws must be modified to account for the perceived directions of points on a surface or of points in monocularly occluded areas. Any account of visual direction must distinguish between absolute and relative directions and between physical and perceptual variables.

1.3 Relevance of the cyclopean eye

Several investigators have claimed that the cyclopean eye is not fixed in the head, but moves along the interocular axis as a function of the stimulus situation (Erkelens, 2000; Erkelens & van de Grind, 1994; Erkelens, Muijs, & van Ee, 1996; Khan & Crawford, 2001; Mansfield & Legge, 1996, 1997). Erkelens and van Ee (2002) assert that the concept of the cyclopean eye is inappropriate and irrelevant. In this dissertation, I will argue that these investigators confused (a) relative (exocentric) direction and absolute (headcentric) direction and/or (b) physical descriptions and perceptual descriptions of direction (Banks, van Ee, & Backus, 1997; Khokhotva, Ono, & Mapp, 2005; Mapp & Ono, 1999; Mapp, Ono, & Khokhotva, 2007; Ono, Lillakas, & Mapp, 2003; Ono, Mapp, & Howard, 2002).

The cyclopean eye is not the location in the head to which perceptually aligned objects physically point. Moreover, inferences about the location of the cyclopean eye cannot be based only on observers' reports that objects appear aligned. Inferences about the location of the cyclopean eye can be made only on reports of where objects lie with respect to the median plane of the head. The task must be a headcentric one. Despite the long history of demonstrations and experiments illustrating this point, some investigators make claims about the location of the cyclopean eye on the basis of relative direction tasks, which do not bear on the question of the location of the cyclopean eye. Indeed, all the studies cited above that claim that the location of the cyclopean eye is stimulus specific are based on only relative direction tasks. For example, Mansfield and Legge (1996, 1997) claimed that the cyclopean eye coincides with the location in the head with which their stimuli were physically aligned. Erkelens et al. (1996) claimed that since the edge of a binocularly seen near surface and the edge of a monocularly seen distant area appeared aligned when they were physically aligned to one eye, the cyclopean eye moved to that eye.

Erkelens and colleagues questioned the validity of the concept of the cyclopean eye (Erkelens & van de Grind, 1994; Erkelens et al., 1996). After conducting a series of experiments using relative direction tasks, they concluded that, "The concept of the cyclopean eye is sometimes inappropriate and always irrelevant as far as vision is concerned." (Erkelens & van Ee, 2002). They claimed that all experiments dealing with this issue since Ptolemy were poorly done and stated that, "Indeed we are astounded that results of many poor experiments from the literature carry so much weight."

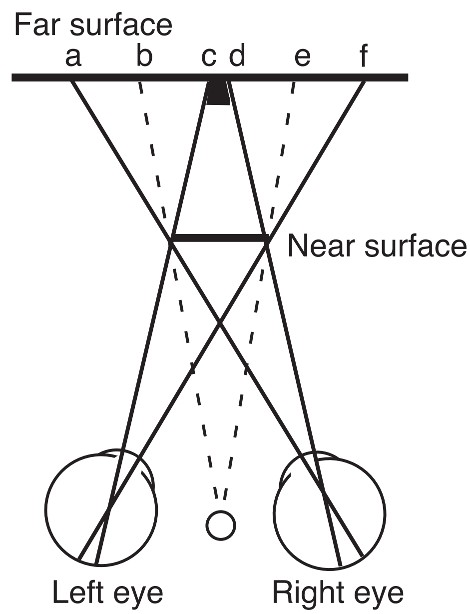

Figure 1.5. Stimulus used by Erkelens and colleagues in their monocular zone experiments (see text).

Figure 1.5 shows the type of stimulus used by Erkelens and colleagues. Note that, since the near surface in the figure partially occludes the distant surface, some of the stimulus elements do not physically project to a cyclopean eye located midway between the eyes. For example, the area from *d* to *e* is visible to the right eye but it is not projected to the centrally located cyclopean eye. Also, note that in the right-eye's view, point *d* is physically aligned with the right edge of the near surface. From a relative direction task Erkelens et al. (1996) concluded that, "binocular space perception near monocularly occluded areas is veridical and the cyclopean eye does not have a fixed position in the head, but is located between the eyes for certain visual directions and in one of the eyes for other directions.” (p. 2145).

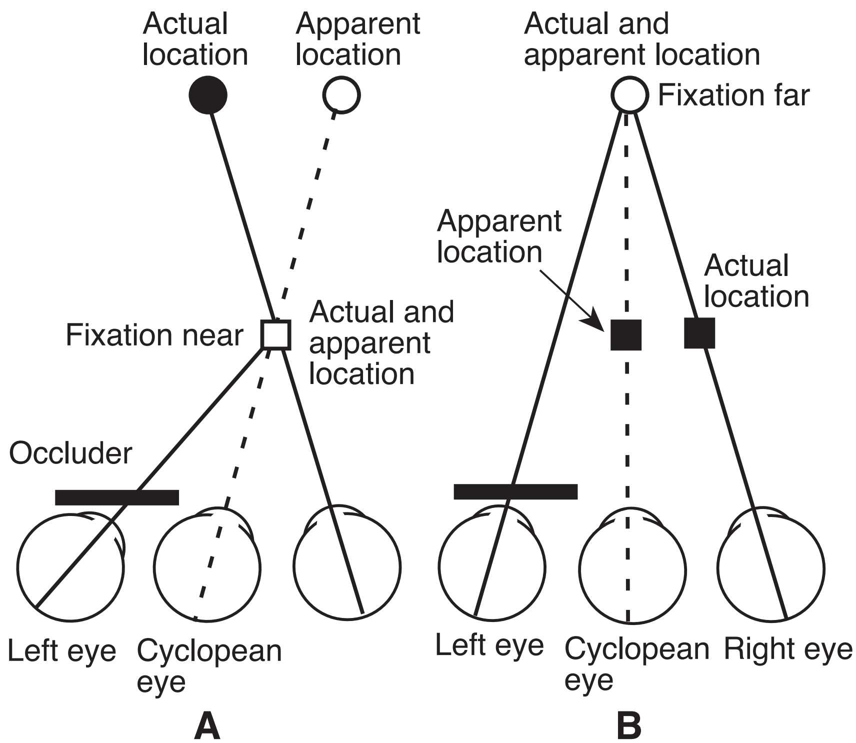

Figure 1.6. The cyclopean illusion. When fixation changes from the near stimulus, as in (A), to the far stimulus, as in (B), the headcentric direction of the far stimulus shifts to the left. The two stimuli on the visual axis of the right eye appear on the cyclopean axis through the point of fixation (dashed lines). The location of the cyclopean axis changes with the change in the point of binocular fixation. Therefore, the concept of the cyclopean eye is needed in explaining the illusion.

Although the monocular zone experiments led Erkelens and his colleagues to conclude that the location of the cyclopean eye is stimulus specific, it was their cyclopean illusion experiment that led them to conclude that the concept of the cyclopean eye is irrelevant. The cyclopean illusion is the apparent shift in the headcentric direction of visual stimuli that occurs when the eyes change convergence, as shown in Figure 1.6. Erkelens (2000) found that with binocular viewing all observers experienced the illusion both in dark surroundings and when the room lights were on. With monocular viewing, however, only 33% of observers experienced the illusion in darkness and none experienced it when the room lights were on. Erkelens concluded that, “perceived direction during monocular viewing is based on signals of the viewing eye only.” (p. 2411). Erkelens and van Ee (2002) concluded that, “The concept of the cyclopean eye is … always irrelevant as far as vision is concerned.”

Erkelens’s conclusions challenge the generally accepted view that judgments of headcentric direction are based on information from the two eyes with both monocular and binocular viewing. The primary purpose of the experiments presented in this dissertation is to examine the validity of this challenge. The general overall hypotheses are that (a) absolute (headcentric) direction judgments of monocularly viewed targets are based on retinal image position and the binocular angular position of the eyes in the head and (b) relative direction judgments only are not sufficient to specify the location of the cyclopean eye.

1.4 The experiments

The experiments in Chapter 3 were conducted in collaboration with Hiroshi Ono and Ian P. Howard (Ono, Mapp, & Howard, 2002). They were designed to (a) measure the relative and absolute (headcentric) directions of monocular stimuli presented on the visual axis of one eye and (b) re-examine the cyclopean illusion under the same monocular and binocular viewing conditions as those used in Erkelens (2000). Based on the laws of visual direction and the overall hypotheses discussed above, it is expected that monocular stimuli, on the visual axis of an eye, will be seen as aligned, not to that eye, but to a point midway between the two eyes. In other words, the stimuli on the visual axis of an eye will transfer to the common (cyclopean) axis under monocular conditions, in the same way as they do under binocular conditions. If this is true, then it is unlikely that the rarity of the cyclopean illusion in Erkelens's monocular conditions is due to headcentric directions during monocular viewing being based on signals of the viewing eye only.

Note from Figure 1.6 that a requirement of the cyclopean illusion is that the left eye (the occluded eye in the figure) rotates when fixation changes between the two stimuli on the visual axis of the right eye. If the left eye remains stationary, then so too does the common axis, and no illusory shift in the headcentric direction of the targets is experienced. Moreover, if the left eye rotates only slightly, the illusion may still not be experienced if the magnitude of the rotation is below some minimum threshold.

It is likely that the rarity of the cyclopean illusion in Erkelens's monocular conditions is due, in part, to the lack of a sufficiently large movement of the common axis. In the monocular conditions, any change in convergence, accompanying the change in fixation of the stimuli on the visual axis of the nonoccluded eye, is evoked primarily by a change in accommodation. An increase in accommodation, when changing fixation from far to near, evokes convergence and a decrease evokes divergence. This coupling of responses, which is known as accommodative convergence can be quantified with the AC/A ratio; the magnitude of accommodative convergence evoked by a one dioptre change in accommodation. There are individual differences in the AC/A ratio and the ratio is known to vary dependent upon how it is measured (Judge, 1985; Judge & Miles 1985; Ripps, Chin, Siegel, & Breinin, 1962). The relevance of this is that the coupling between accommodation and convergence is not perfect, and therefore it is unlikely that the eyes converge accurately on monocularly viewed targets. Moreover, the magnitude of this misconvergence, as measured by phoria, ("the direction or orientation of one eye, …in relation to the other eye, manifested in the absence of an adequate fusion stimulus…" (Cline, Hofstetter, & Griffin, 1989, p. 529) has been shown to vary as a function of fixation distance (Barbeito & Simpson, 1991; Holland, 1958; Ono & Weber, 1981). A consequence of this is that when changing fixation from one distance to another, the common axis moves through a lesser extent with monocular viewing than with binocular viewing, where any misconvergence due to fixation disparity would be significantly smaller. Figure 3.6 illustrates the expected reduction in the extent of the cyclopean illusion with monocular viewing as a result of phoria.

The experiments in Chapter 4 were conducted in collaboration with Hiroshi Ono and Haruki Mizushina (Ono, Mapp, & Mizushina, 2007). In these experiments the cyclopean illusion was re-examined under monocular viewing conditions in which convergence changes evoked by changes in accommodation were greater than those in the experiments in Chapter 3. Additionally, the stimuli were viewed against four different background patterns. Two of the backgrounds contained salient reference points or landmarks that "anchored" the relative directions of the stimuli (the near and far LEDs) with respect to the background, and two other backgrounds contained no such landmarks. The magnitude of the cyclopean illusion in the "anchoring" conditions is expected to be smaller than in the "non-anchoring" conditions. It is likely that such an anchoring effect also contributed to the rarity of the cyclopean illusion reported in Erkelens (2000).

The experiments in Chapter 5 were conducted in collaboration with Hiroshi Ono and Mykola Khokhotva (Mapp, Ono, & Khokhotva, 2007). In these experiments absolute and relative direction judgments were examined using laser gun aiming and dart throwing tasks. Based on the laws of visual direction and the overall hypotheses discussed above, it is expected that the accuracy of absolute direction judgments only will depend upon eye position. Additionally, it is binocular eye position information that is predicted to be crucial, independent of whether the absolute direction judgement is performed binocularly or monocularly.

The results from the experiments reported here will (a) shed light on some contradictory reports in the literature, (b) clarify the distinction between relative and absolute visual direction, and (c) aid in the development of a more comprehensive theory of how visual directions specified from the cyclopean eye (perceptual variables) are derived from the inputs from the two eyes (physical variables).

Chapter Two: Wondering About the Wandering Cyclopean Eye*

* Mapp, A. P., & Ono, H. (1999). Wondering about the wandering cyclopean eye. *Vision Research, 39,* 2381-2386. doi:10.1016/S0042-6989(98)00278-8

Abstract

Arguments against claims (Erkelens et al.,1996; Mansfield & Legge, 1996, 1997) that the position of the cyclopean eye is stimulus specific are presented. Critical to these arguments are the differences between relative and absolute visual direction tasks (Howard, 1982; Ono & Mapp, 1995), and between physical and perceptual descriptions of visual direction (Ono et al., 1998; Ono & Lillakas, 1997).

Introduction

To judge the visual directions of objects a centre or origin like that of a polar coordinate system in plane geometry is required. The concept of this origin is both a logical and a functional necessity, not only for judging the direction of one object with respect to another (a relative direction task), but also for judging the direction of objects with respect to oneself (an absolute direction task). Over the years this origin has been referred to, amongst other things, as the binoculus, the egocentre, the double eye, the projection centre, the centre of visual direction, and the cyclopean eye. In this letter, we use the term "cyclopean eye".

Recently, Mansfield and Legge (1996) claimed that the cyclopean eye wanders along the interocular axis. Banks et al. (1997), immediately responded with the argument that since Mansfield and Legge used a relative direction task their data do not bear upon the location of the cyclopean eye. We agree fully with Banks et al.'s critique; however, an extension of their argument is required for several reasons. First, Mansfield and Legge are not the only investigators to inadvertently make claims about the location of the cyclopean eye based upon a relative direction task. For example, Erkelens et al. (1996) also claimed, based upon a relative direction task, that the cyclopean eye is not fixed and then used this idea in the context of what they called "capture of binocular visual direction" (Erkelens & van Ee, 1997a, 1997b). Second, Mansfield and Legge's (1997) response to Banks et al. introduced a confusion between physical and perceptual descriptions of visual direction. Third, although the theoretical implications of a wandering cyclopean eye are interesting, Erkelens et al.'s data are explainable without postulating that the cyclopean eye is a wanderer.

Visual Direction Task Confusion Revisited[1]

As evidenced by a common misconception in the ocular dominance literature, it is incorrect to assume that the cyclopean eye coincides with the location on the face to which two perceptually aligned objects physically point. In the Card Test, for example, an observer is asked to sight an object that can be seen with only one eye, through a hole in a card, (i.e., s/he is asked to perform the relative direction task of aligning the hole with the object), and it is inferred that the dominant eye is the centre from which the visual directions are judged (Parson, 1924; Porac & Coren, 1981; Rubin & Walls, 1969; Sheard, 1926; Walls, 1951). The data from our laboratory, obtained from observers pointing with unseen hand, (an absolute direction task), clearly show that this inference is incorrect (Ono & Barbeito, 1982). These data are shown in Figure 2.1, together with Hering's well known demonstration of the law of identical visual direction.

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[1] For definitions of "relative direction" and "absolute direction", see Cline, Hofstetter, and Griffin (1989, pp. 190–191). We chose the term "relative", rather than "oculocentric" or "alignment", to avoid the implication that the cyclopean eye is located in an eye. We chose the term "absolute", rather than "egocentric", "headcentric", or "bodycentric", so as to parallel and contrast the term "relative".

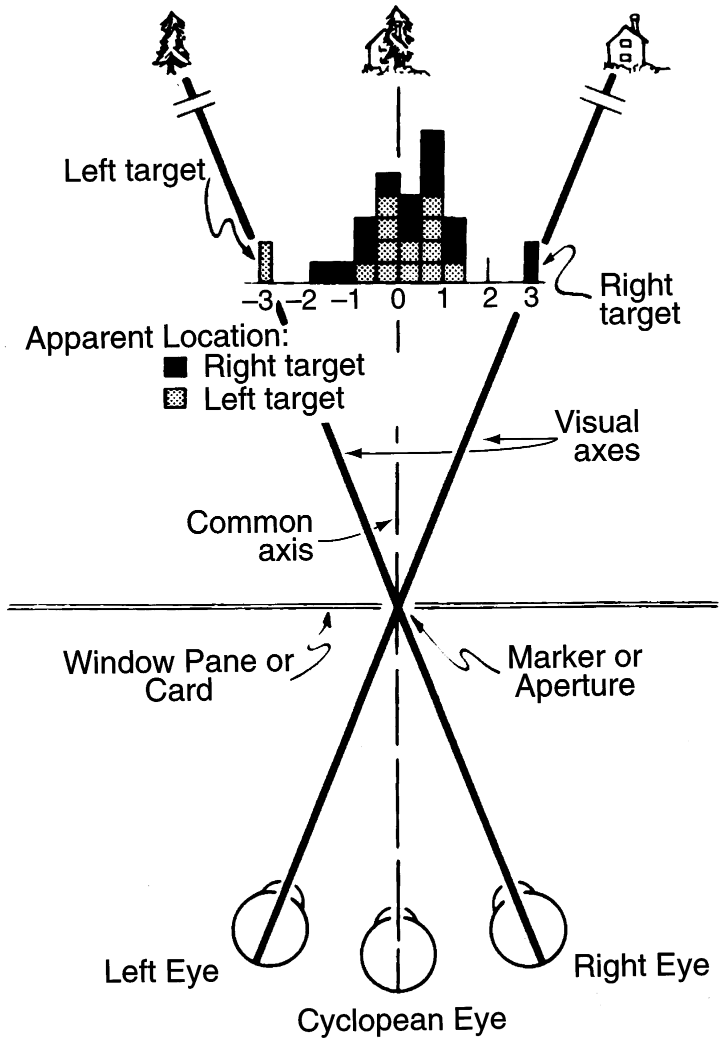

Figure 2.1. Illustration of the experimental stimuli and the results from Ono and Barbeito (1982). The results are superimposed on Hering's demonstration of the law of identical visual direction to show that they are congruous with the well known phenomenon that stimuli on a visual axis appear on the common axis (i.e., the line which passes through the intersection of the two visual axes and the cyclopean eye). The card and the targets were located at 25 cm and 50 cm, respectively. Observers indicated the apparent location of the target by moving the handle of a slider under the table with unseen hand. Adapted from Ono and Barbeito (1982).

The data and the demonstration presented in Figure 2.1 indicate that objects which are physically collinear with respect to an eye, appear collinear with respect to the centrally located cyclopean eye. Ono and Barbeito (1982) asked observers to report the absolute directions of a perceptually aligned hole and target by pointing with unseen hand under a table. They found that the line passing through these two perceived locations did not pass through the eye to which they were physically aligned, but rather it passed through a point approximately midway between the eyes. Similarly, in Hering's demonstration a perceptually aligned marker and tree (or chimney) appeared straight–ahead of the nose when the marker was fixated. These findings clearly show that the centre from which visual directions are judged (i.e., the cyclopean eye) is located approximately midway between the eyes. Moreover, they demonstrate that inferences about the location of the cyclopean eye cannot be based on observers' reports that two visible objects appear aligned (a relative direction task). To make inferences about the location of the cyclopean eye, observers must report where the objects appear with respect to themselves (i.e., they must perform an absolute direction task such as pointing with unseen hand).

The inferences made by Mansfield and Legge (1996, 1997) and Erkelens et al. (1996) are analogous to the inferences made about the dominant eye. Mansfield and Legge (1997) claimed, that since their stimuli were physically aligned to the point positioned between the midpoint of the interocular axis and one of the eyes, the "effective viewpoint" moved to that location. Similarly, Erkelens et al. claimed, that since the edge of the binocularly seen near surface and the edge of the monocularly seen area appeared aligned when they were physically aligned to one eye, the cyclopean eye wandered to that eye. Neither of these claims can be made based on their data.

If Mansfield and Legge (1996) had measured the absolute directions of the five stimuli in Figure 6 of their paper, an inference about the location of the cyclopean eye could be made. For example, if the five points had the same absolute visual direction, then the line passing through them would also pass through the cyclopean eye. Such an inference would be the same as in Howard and Templeton's (1966) method in which two points, presented successively, and judged to have the same absolute direction, are thought to point to the cyclopean eye.

Likewise, if Erkelens et al. (1996) had measured the absolute direction of relevant points, an inference would be possible. Such an inference would be the same as in Roelofs's (1959) method in which two stimuli are made objectively collinear to one eye, and observers are asked to indicate where on their face the imaginary line passing through the stimuli appears to point. This location on the face defines the position of the cyclopean eye. (For other methods of measuring the position of the cyclopean eye see, for example, Barbeito & Ono, 1979; Howard & Templeton, 1966; Mitson et al., 1976.)

Physical versus Perceptual Descriptions of Visual Direction

To address Mansfield and Legge's (1997) response to Banks et al. (1997) and to elaborate on Erkelens et al.'s (1996) claim of a non–fixed cyclopean eye, we present a distinction between the "eye's view", the "camera view", and the "cyclopean view". (See Ono et al., 1998; Ono & Lillakas, 1997). Within each of these views, the directional lines of objects in the visible field intersect at a point analogous to the origin of a polar coordinate system. For the eye's view this point is the nodal point of the eye, and for both the camera view and the cyclopean view it is the midpoint between the eyes on the Vieth–Müller horopter. The term eye's view describes the directions of the elements in the visual field which are visible to only the left eye or only the right eye. The term camera view describes the directions of the elements in the visual field which would be contained in a photograph taken by a camera positioned midway between the eyes. The term cyclopean view describes the total set of visual directions of the elements visible to the left eye, the right eye, or both eyes, (i.e., the two eyes' views), which are transferred to a fixed cyclopean eye midway between the eyes.

How this distinction applies to Mansfield and Legge (1997).

Mansfield and Legge, in their response to Banks et al. (1997), made a distinction between the cyclopean eye and what they called the effective viewpoint. From their discussion, however, it appears that they confounded these ideas. For example, they define effective viewpoint as "the physical location from which objects are viewed" (p. 1611). This definition is analogous to our definition of the eye's view and implies to us either one or the other of the two physical eyes. Yet, they claim that their data indicate that the effective viewpoint moved to a location closer to the eye viewing the higher contrast image. This claim indicates to us that they have confounded the effective viewpoint (a physical vantage point), with the cyclopean eye (a perceptual vantage point). Therefore, their claim that the effective viewpoint moves, is no different than their original claim (Mansfield & Legge, 1996) that the cyclopean eye moves, and, as such, it is subject to all the same criticisms discussed by Banks et al.

Given this distinction, it is clear that Mansfield and Legge's (1996) interesting conclusion, namely, relative direction is affected by interocular contrast–ratios, does not require the assumption of a non–fixed cyclopean eye. Indeed, postulating that the cyclopean eye wanders to the location collinear with the perceptually aligned targets precludes Mansfield and Legge (1996, 1997) from concluding that their targets appeared in different visual directions. This idea is best understood by thinking of the cyclopean eye as the origin of a polar coordinate system. In such a system, any two points which are connected to the origin by a single straight line share a common directional value. Conversely, any two points which are not connected to the origin by a single straight line differ in directional value. Moreover, regardless of the locus of the origin, if two points and the origin fall on a single straight line then, by definition, the two points share a common directional value with respect to the origin. How these ideas apply to Mansfield and Legge's argument is presented below.

Consider two equal–contrast targets presented, one above the other, at different stereoscopic depths. It is widely accepted that such targets appear in the same visual direction (i.e., the two perceived targets and the cyclopean eye [the origin] fall on a single visual direction line). If one of the equal–contrast targets is replaced with a mixed–contrast target, then, as reported by Mansfield and Legge (1996), the two targets no longer appear aligned. In other words, the two perceived targets and the cyclopean eye (the origin) no longer fall on a single visual direction line and, therefore, the targets appear in two different visual directions. It is true, however, that the two perceived targets and the effective viewpoint, as defined by Mansfield & Legge (1997), fall on a single line. By postulating that the effective viewpoint is the origin or the centre of visual direction, Mansfield and Legge (1996, 1997) must conclude that the two targets have the same visual direction (i.e., the two targets and the effective viewpoint [the origin] fall on a single visual direction line). Thus, Mansfield and Legge (1996, 1997) cannot conclude that their targets were seen in different visual directions if they simultaneously claim that the cyclopean eye wandered to the position collinear with the two perceived targets.

How this distinction applies to Erkelens et al. (1996).

Figure 2.2 illustrates Erkelens et al.'s stimulus situation. Note that since the near surface partially occludes the distant surface some of the elements contained in the eyes' views (Panel A) are not in the camera view (Panel B). For example, the area from (d) to (e) is contained in the right eye's view, but not in the camera view. Also, note that in the right eye's view, point (d) is physically aligned with the right edge of the near surface. The basis of Erkelens et al.'s argument is that, since point (d), which is not in the camera view, and the right edge of the near surface are judged to be collinear, the cyclopean eye must move to the right eye when making this judgment. To counter this idea, however, note that point (d) is conceptually equivalent to the target seen through the hole in the card in Figure 2.1. That is, point (d) is not in the camera view just as the left target would not be in the stimulus situation depicted in Figure 2.1. Therefore, if we were to apply Erkelens et al.'s idea to the stimulus in Figure 2.1, we must argue for a wandering cyclopean eye for that stimulus as well. In contrast, if we were to apply Hering's law to predict the apparent direction of (d) when fixation is on the near surface, we must argue that (d) is displaced to (d') and seen from the fixed cyclopean eye as shown in Panel C. In this interpretation, one need not postulate a wandering cyclopean eye.

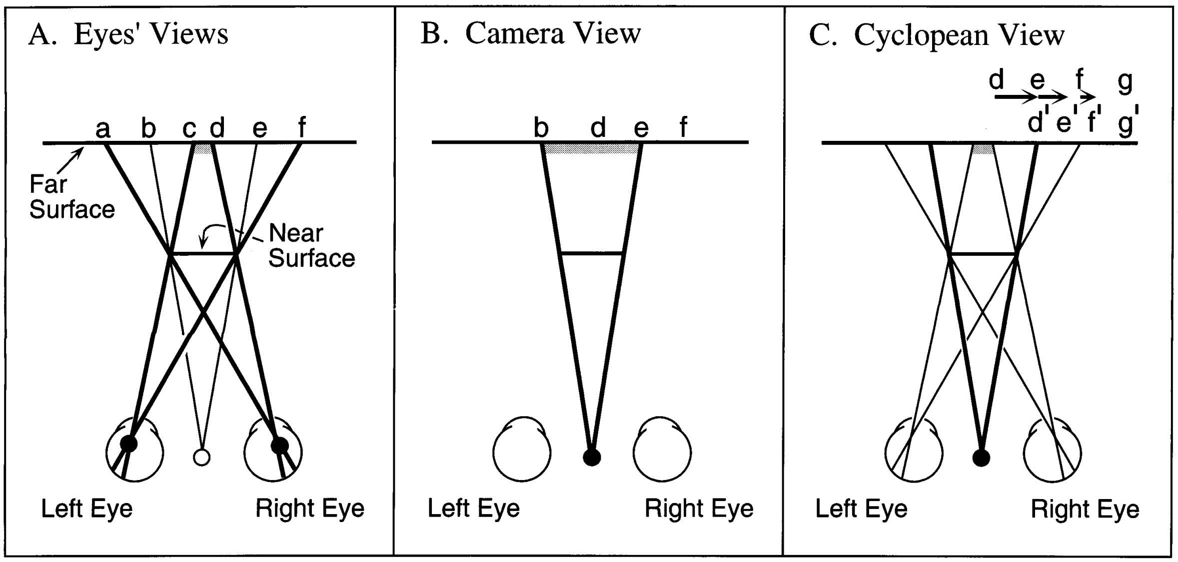

Figure 2.2. Illustration of the two eyes' views, the camera view, and the cyclopean view for Erkelens et al.'s (1996) stimulus. In the cyclopean view, point (d) is displaced rightward to (d') as was the left target in Figure 2.1, and the area (d) to (g) shrinks to fit into the area (d') to (g'). This compression is indicated by the distance between (d') to (g') being smaller than the distance between (d) to (g). Note that similar displacements and compressions occur in the areas seen monocularly by the left eye, but to simplify the Figure they are not illustrated.

Visual Direction with a Fixed Cyclopean Eye

Although Figure 2.2 shows that there is no need to postulate that the cyclopean eye wanders, it also illustrates that Hering's idea of cyclopean projections is inadequate (see Erkelens & van de Grind, 1994; Ohtsuka, 1995b; Ohtsuka, Kawanura, & Kosugi, 1990; Ono & Lillakas, 1997; van de Grind et al., 1995). The inadequacy is that the visual angle subtended by the monocularly seen areas (depicted in Figure 2.2) is too large to fit into the cyclopean view, if the areas seen binocularly are perceived correctly, as stated in Hering's laws of visual direction. For this angle to fit, the monocular area labelled (d) to (f) in Panel A of Figure 2.2 must fit into the area labelled (e) to (f) in Panel B, which it obviously cannot. One possible solution is to discard the area labelled (d) to (e) in the right eye's view from the cyclopean view, which has the advantage that the visual directions of the binocular areas are perceived correctly, as in the camera view. However, the visual system does not employ this solution because, as discussed above and as reported in the literature (e.g., Erkelens et al., 1996; Ono et al., 1998; Ono & Lillakas, 1997) all of the monocular areas are seen.

How does the visual system solve this problem? One hypothesis is that the eyes' views are seen in their entirety, but some areas in the non–fixated plane are displaced and compressed. (To adjust for the consequences of this displacement and compression, namely, misalignment of lines and deformation of shape, the visual system has a "correcting" mechanism which is triggered by the pictorial cue of occlusion. See Ohtsuka, 1995b; Ohtsuka & Yano, 1994; or Ono et al., 1998 for a discussion.) The predictions from this hypothesis, when the near surface is fixated, are illustrated in Panel

C of Figure 2.2. Evidence of displacement of a monocular area on a non–fixated plane has been available for nearly two millennia[2], and evidence for compression in non–fixated areas, is now available (Ohtsuka, 1995a; Ohtsuka & Yano, 1994; Ono et al., 1998; Ono & Lillakas, 1997). Erkelens et al. (1996) suggested a hypothesis similar to this one but then, without controlling for fixation, argued that it is more likely that the following two suggestions are true: (a) "binocular space perception near monocularly occluded areas is veridical" and (b) "the cyclopean eye does not have a fixed position in the head..." (p. 2145). To make suggestion (a), they must employ an absolute direction task with fixation control, as used to collect the data presented in Figure 2.1. Hering's laws of visual direction predict veridical visual direction for the far surface when the intersection of the visual axes is on it, without assuming that the cyclopean eye has shifted to one of the eyes. Therefore, suggestion (a) may be correct when fixation is on the far surface. When fixation is on the far surface, however, there is a compression of the near surface (Ohtsuka, 1995a; Ono et al., 1998). To make suggestion (b), they must also employ an absolute direction task, not a relative direction task.

Summary and Conclusion

The analyses presented in this letter show that neither Mansfield and Legge's (1996, 1997) nor Erkelens et al.'s (1996) data are sufficient to conclude that the

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[2] This has been known since the time of Ptolemy, circa 100–170 AD (see Howard & Wade, 1996), and was observed, for example, by Alhazen (1083/1989), Hering (1879/1942), LeConte (1871), and Wells (1792), and was discussed by Howard (1996) recently.

cyclopean eye is a wanderer. Moreover, our analyses show that their data are explainable without the assumption of a wandering cyclopean eye. Given that the cyclopean eye shifts in monocularly enucleated people (e.g., Dengis et al., 1998; Dengis et al., 1993; Moidell et al., 1988), and that there are individual differences in its position in binocular people (e.g., Barbeito, 1981; Barbeito & Simpson, 1991), the claim that its position is stimulus specific is both conceivable and worthy of consideration. However, the theoretical implications of a fixed, non–central cyclopean eye differ from those of a stimulus specific, wandering cyclopean eye. With a fixed cyclopean eye, be it located centrally or non–centrally, the origin about which all visual directions are specified remains fixed. With a wandering cyclopean eye, the origin changes with every change in stimulus situation and, therefore, the directions of objects with respect to the observer must be recalibrated continually. Thus, if one postulates a wandering cyclopean eye, one need also specify how this recalibration of visual space is accomplished. Based on the arguments presented in this letter, however, there is no need to speculate on how this recalibration is accomplished, because to date there are no compelling data to suggest that the cyclopean eye is a wanderer.

Chapter Three: The Cyclopean Eye in Vision: The New and Old Data Continue to Hit You Right Between the Eyes*

* Ono, H., Mapp, A. P., & Howard, I. P. (2002). The cyclopean eye in vision: the new and old data continue to hit you right between the eyes. *Vision Research, 42,* 1307–1324. doi:10.1016/S0042-6989(01)00281-4

Abstract

We argue against claims by Erkelens and van Ee (2002) and by Erkelens (2000) that “the concept of the cyclopean eye is … always irrelevant as far as vision is concerned” (p. 1157) and that “perceived direction during monocular viewing is based on the signals of the viewing eye only" (p. 2411), respectively. In Experiment 1, we presented a pair of small lights on a visual axis and measured the absolute visual direction of the near light with reference to different parts of the face. The near light appeared in front of the bridge of the nose or very near it, contrary to what was expected from Erkelens and van Ee's claim that monocular stimuli are seen in their correct locations. In Experiment 2, we replicated Erkelens’s experiments with measurements of phoria and analyses of eye movements. The results confirmed his finding that the cyclopean illusion occurred rarely in the monocular condition, but our phoria and eye movement data provided the basis for a very different interpretation. Our data show that the oculomotor signal in his particular monocular condition was considerably weaker than in his binocular condition; therefore, the rarity of the monocular cyclopean illusion is not surprising. Moreover, since both claims above are based on an over-generalization of the results of Erkelens’s study, neither claim is persuasive.

Introduction

The generally accepted view on how the inputs from our eyes are combined to yield a percept of the direction of objects with respect to ourselves has been challenged by Erkelens and van Ee (2002) and Erkelens (2000). To date, the literature has shown that the physical information of both eyes is combined in such a way that we perceive the directions of objects as though we were viewing the world from an imaginary eye (the cyclopean eye) positioned midway between our eyes. That is, the two eyes operate not as two separate organs but as two halves of a single organ (Hering, 1868/1977). Because any valid challenge to an accepted view in science signifies progress, the two claims described in the abstract offer an exciting possibility for advancements in visual science. Any such challenge should not be taken lightly, however, but should be subjected to careful scrutiny. In this paper we examine the two claims and we argue that they are invalid and unwarranted. We contend that Erkelens and van Ee’s claim is incorrect when visual direction is operationally defined, and the domain of the concept of the cyclopean eye is made explicit, and that Erkelens’s claim is untenable when the differences between his binocular and monocular conditions are examined closely. We support our contentions with two experiments.

In Experiment 1, we explore and clarify two possible meanings of perceived direction and we examine how each meaning relates to Erkelens and van Ee’s (2002) claim. The two possible meanings are absolute and relative direction as discussed recently by Mapp and Ono (1999). Based on the results of this experiment and the visual direction literature, we argue that Erkelens and van Ee's claim applies to relative direction but not to absolute direction: we maintain that the concept of the cyclopean eye is necessary in dealing with absolute direction.

In Experiment 2, we explore an alternative interpretation of Erkelens's (2000) finding that the cyclopean illusion (see Figure 3.1) occurs less frequently under monocular viewing conditions than binocular conditions. Specifically, we show that with his stimulus configuration, the eye movement signal is weaker (smaller and slower) in his monocular condition than in his binocular condition, consistent with Erkelens and Regan's (1986) finding that "as for the relative effectiveness of disparity *(binocular)* and accommodation *(monocular)* in driving ocular vergence, disparity has been shown to be considerably stronger" (p. 146; italics ours). The weak oculomotor signal is responsible, in part, for the difficulty in detecting the change in absolute direction in his particular monocular condition. We point out that his claim is based on a finding specific to his monocular condition and is incompatible with what is reported in the literature. We also point out that there is another factor that contributes to the difficulty in detecting the change in absolute direction in the monocular condition, namely, the relative direction of the stimulus with respect to the stable background remains constant.

Both experiments reported here are relevant to our two contentions, but Experiment 1 more directly addresses the issues raised by Erkelens and van Ee (2002) and Experiment 2, the issues raised by Erkelens (2000). Experiment 1 shows that two monocular stimuli on the visual axis of one eye (instead of one binocular and one monocular as shown in Figure 3.1) appear on the common axis. That is, two monocular stimuli that are physically aligned with the viewing eye appear collinear, not with respect to that eye, but with respect to the cyclopean eye, and thus at least one of the two stimuli is seen in a non-veridical location. Experiment 2 replicates Erkelens's finding that only a minority of observers experience the cyclopean illusion in a monocular condition comparable to his. However, our measurement of the phoria associated with the stimuli and a more complete analysis of the eye movements, provide the basis for a quite different interpretation.

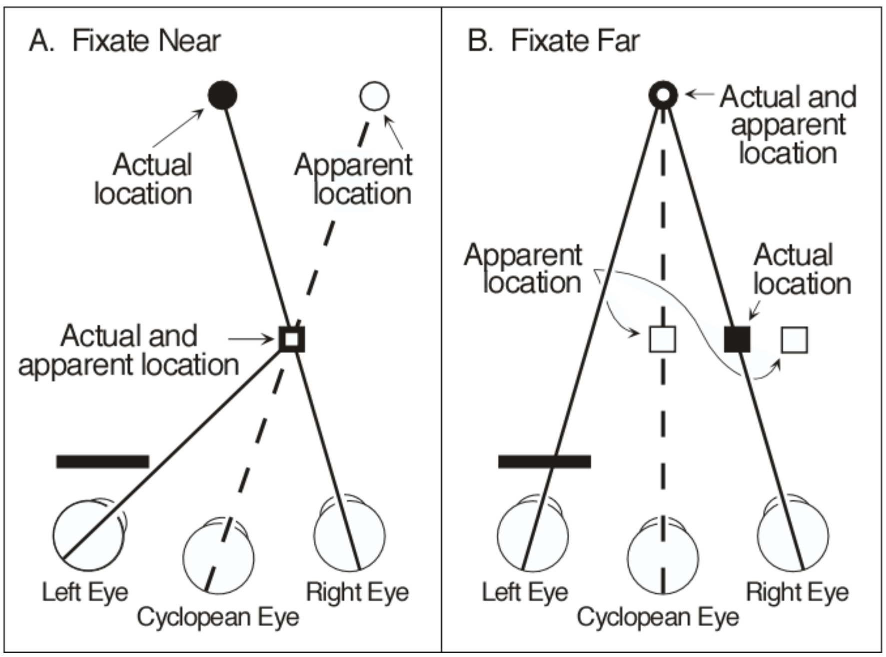

Figure 3.1. Illustration of the cyclopean illusion as studied by Erkelens (2000). When fixation changes from the near stimulus (Panel A) to the far stimulus (Panel B) the absolute visual direction of the far stimulus shifts to the left. The two stimuli on the visual axis of the right eye are seen on the common axis (dashed lines). The near stimulus is seen as double when the far stimulus is fixated. The explanation of the illusion is that stimuli on the visual axis (or on a visual line) appear on the common axis (or on the cyclopean line) and that the location of the common axis (or the cyclopean line) changes with the change in binocular eye position. Note that the common axis is defined as a line passing through the intersection of the visual axes and the cyclopean eye, and therefore the concept of the cyclopean eye is needed in explaining the illusion.

Experiment 1

The basic phenomenon demonstrated is not new; Ptolemy (circa 100 – 170 AD) knew it (Howard & Wade, 1996). The phenomenon where stimuli on the visual axis of one eye appear on the common axis has been shown repeatedly throughout history. For example, Alhazen (1083/1989) showed it using lines on a board (see also Howard, 1996), Wells (1792) showed it using wires and string or two holes in a sheet of paper, and Hering (1879/1942) showed it as discussed shortly. In each of these examples, viewing was binocular and, therefore, binocular fusion of at least one stimulus and diplopia of a different stimulus were involved. In this experiment we show that this phenomenon is as robust under monocular viewing conditions, without fusion or diplopia, as it is under binocular conditions.

The critical stimulus in Experiment 1 was presented very close to the observer's face, thereby allowing for easy judgements of both its absolute and relative directions. Observers could report its absolute direction with reference to different parts of their face, for example, in front of their nose, between their eye and their nose, or in front of their eye, and they could also report its relative direction with respect to a more distant stimulus. In this experiment we presented two stimuli on the visual axis of one eye. We did this in six different viewing conditions in which, according to Erkelens and van Ee (2002), the critical stimulus should be seen directly in front of the eye. We had two viewing conditions that Erkelens (2000) did not have: the monocular stimuli were presented to each eye simultaneously without a binocular stimulus. According to their hypothesis, the critical stimulus for each eye in these conditions should also be seen directly in front of the eyes despite the fact that the two stimuli have the same horizontal local sign.

The purpose of this experiment is to (a) clarify the distinction between absolute and relative direction, (b) specify what inferences can and cannot be made on the basis of relative direction tasks, and (c) show that two targets collinear with one eye cannot be seen, simultaneously, in their veridical locations. These three aims are identical to those of Mapp and Ono (1999), who argued against Erkelens et al. (1996) claim that the cyclopean eye moves to the viewing eye. All of the arguments by Mapp and Ono apply equally to Erkelens and van Ee (2002), since their claim is the same as before with the exception that they do not use the term cyclopean eye. That is, their claim that with monocular viewing all stimuli on the visual axis (or visual line) are seen on that axis (or line), is identical to their claim that the cyclopean eye moved to the viewing eye. Hopefully, the inclusion of experimental evidence with our arguments in this paper will clarify this point. [3]

This experiment also addresses the following empirical question raised by Erkelens and van Ee (2002): what are the absolute visual directions of stimuli, collinear

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[3] In this paper we do not address Erkelens and van Ee's (2002) argument against the use of the cyclopean eye concept when dealing with the visual directions of monocularly seen areas (section 5 of their paper). A more complete description of Ohtsuka and Ono's (1998) hypothesis can be found in Ono et al. (1998), Mapp and Ono (1999), and Ono, Wade, and Lillakas (2002), and more empirical papers are in preparation. Readers are referred to these published papers to judge the merit of the hypothesis in contrast to the Erkelens and van Ee hypothesis.

with one eye, when they are presented monocularly? This question is an important one, because Erkelens and van Ee's claim and Erkelens's (2000) claim are based on the assumption that monocular stimuli are seen in their correct absolute directions, and answering this question should resolve the theoretical disagreement. Our understanding of Erkelens and van Ee's position is that they predict that monocular stimuli presented on a visual line of one eye would be seen on that line and aligned with that eye. Their idea is discussed in the context of Hering's (1879/1942) classical demonstration in which a tree-top and a chimney (one on each visual axis) appear straight-ahead of the nose, while binocularly fixating on a spot on a window pane. According to their claim, these stimuli appear straight-ahead of the nose because of the averaging of two "vectors", one specified from each eye. When the stimuli are presented monocularly, however, there is no averaging and their prediction is that the tree-top or the chimney is no longer perceived straight-ahead of the nose (i.e., on the common axis), but rather they appear on the visual axis. As has been shown in the literature and as we will show again in Experiment 1, this prediction must be rejected.

Methods

Observers

All 12 observers were naïve as to the purpose of the experiment. They ranged in age from 21 to 43 years. Six were unfamiliar with psychophysical or eye movement experiments, but six had participated in many such experiments.

Stimuli and Apparatus

The stimuli, similar to those used by Erkelens (2000), were four small light emitting diodes (LED's) presented monocularly. Two of them, one for each eye, were presented approximately 2 cm from the cornea. The other two, again one for each eye, were positioned 30 cm from the observer's cornea. These four green LEDs (Chicago Miniature IDI 5370T5) were separated vertically so that the far right one was the highest followed by the far left, the near right, and the near left. Each LED was seen monocularly because of the arrangement of the four sheets of Polaroid filters as shown in Figure 3.2. The observer could move the two far LEDs together in the frontal plane, inwardly or outwardly, by turning a knob. A pinhole pierced in a sheet of aluminium foil was placed in front of each near LED to reduce its angular size. The observer could move the near LEDs independently by turning two knobs attached to each of the LEDs. One knob moved the LED laterally (leftward or rightward) and the other moved it sagittally (forward or backward). The observer's head was stabilized with a biteboard.

Pre-experimental procedure

The four LEDs were adjusted as follows. First, the experimenter positioned one of the near LEDs 2 cm in front of the observer's right eye, and confirmed that it could not be seen by the left eye. This was repeated for the near LED in front of the left eye. Second, the two far LEDs were turned on (one was seen by each eye) and the two near ones turned off. The observer turned the knob attached to the far LEDs until both were seen in the same horizontal direction. That is, one was seen above the other. Third, the pair of LEDs for one eye (one near and one far) was turned on, and the observer adjusted the lateral position of the near until the two appeared in the same horizontal direction. The same procedure was repeated for the pair of LEDs for the other eye.

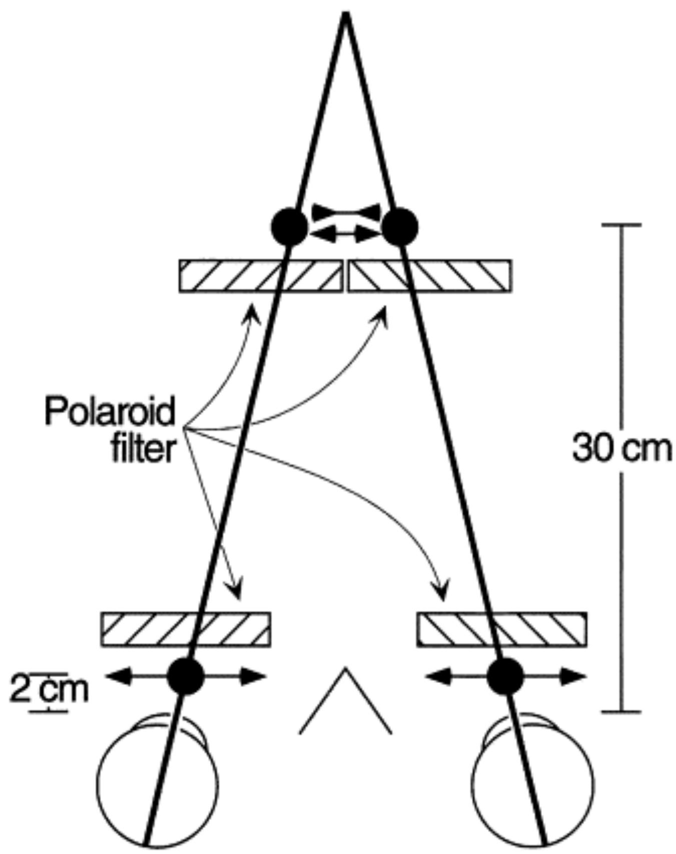

Figure 3.2. Schematic drawing of the stimulus arrangement in Experiment 1. The bold arrows indicate the directions in which the stimuli could be moved. The near stimuli could also be move forward and backward but to simplify the figure this movement is not illustrated.

Experimental procedure

Data were collected from each observer under each of three viewing conditions and two room light conditions. The three viewing conditions were (a) *double monocular*, in which both eyes were open and all four LEDs were presented, (b) *monocular with two eyes open*, in which only the pair of LEDs for the right eye or the pair for the left eye was presented, and (c) *monocular with one eye closed*, in which the pair for the right eye or the pair for the left eye was presented as in (b), but the eye to which the stimuli were not aligned was closed. The two room light conditions were (a) the *bright room* condition, in which parts of the apparatus such as the optic benches, the stimulus holders, and the wall behind the apparatus were visible, and (b) the *dark room* condition in which only the stimulus lights were visible. The six possible orders of presenting the three viewing conditions were combined with the two possible orders of room light conditions for 12 different observers. The three viewing conditions were presented as a block in the bright room condition and the dark room condition. For the first block, the pair of LEDs for the right eye and the pair for the left eye were presented in random order in viewing conditions (b) and (c). Before starting the second block, the alignments discussed in the pre-experimental procedure were checked, then the pair that was not used in the first block was presented.

After each stimulus presentation, the observers were asked to come off the biteboard and to report the relative direction of the near LED(s) with respect to the far one(s), (e.g., directly below the top one) and the absolute direction of the near LED(s), (e.g., in front of the nose, in front of the eye, or between the eye and the nose and by how much). In reporting the absolute direction, they were told to report where the near LED appeared to be located rather than where they knew it to be located. After reporting the two different visual directions, they were asked to get back on the biteboard and to close their eyes while the stimulus was changed for the next condition.

Results and Discussion

The reported absolute direction of the near LEDs is presented in Table 3.1. The table clearly shows that the near LEDs were rarely seen in front of either eye, contrary to what was expected from Erkelens and van Ee's (2002) claim. There were only two such reports out of the 72 reports made by the 12 observers. The most common report was that the near LED appeared either directly in front of the nose or very near the middle of the bridge of the nose. When the near LED was reported to appear close to the nose, the observer was asked to point to where it appeared on the face. All such observers pointed to a part of the bridge of their nose. Specifically, all 12 observers reported that the near LEDs appeared in front of the nose or near it in the double-monocular condition. The number of observers who reported “directly in front of the nose” decreased slightly in the other two conditions and the number of observers who reported "closer to the nose" increased.

Table 3.1. Frequencies of absolute direction responses in the six conditions in Experiment 1.

Monocular viewing condition	Absolute direction response categories in two room light conditions					
	Directly in front of the nose or (close to the nose)		In between the nose and an eye		Directly in front of an eye or (close to an eye)	
	Bright	Dark	Bright	Dark	Bright	Dark
Double	12 (4)	12 (6)	0	0	0	0
Two eyes open	12 (6)	11 (10)	0	0	0	1 (1)
One eye closed	10 (9)	10 (7)	0	1	2 (1)	1

As also indicated in Table 3.1, there were no systematic differences between the bright and the dark room conditions. (This lack of difference, especially in the one eye closed condition, is inconsistent with Erkelens's (2000) hypothesis that the difference in luminance between the two eyes suppresses the oculomotor signals of the closed eye.) Therefore, we combined these two conditions before computing an index of where, on average, the near LED appeared (i.e., its absolute direction) across observers. We assigned the values 0, 1, 2, 3, and 4, to "in front of the nose", "close to the nose", "in between the nose and an eye", "closer to an eye", and "in front of an eye", respectively. For the double monocular condition, we ignored the direction of deviation in the analysis. (For all but one of the observers that reported "close to the nose", the deviations were toward the left.) In the other two viewing conditions, we assigned positive values to deviations toward the viewing eye. There were no deviations toward the non-viewing eye. The computed means and (standard deviations) of these values across the different observers were .42 (.42), .83 (.49), and 1.17 (.75) for the double, two-eyes-open, and one-eye closed conditions, respectively. An analysis of variance for correlated observations showed that the differences between the conditions were statistically significant at $p = .006$, and a Tukey's (HSD) test indicated that the mean of the absolute direction in the double monocular condition was significantly different from that of the one-eye-closed condition with $p < .01$.

Our finding, that several of the observers did not see the near LED precisely in the middle of the bridge of their nose in the double-monocular condition, reflects individual differences in the location of the cyclopean eye (e.g., Barbeito, 1981, Barbeito & Ono, 1979.) The tendency for the near LED to appear deviated slightly toward the viewing eye in the two-eyes-open condition and in the one-eye-closed condition is probably related to an unequal weighting of the eyes (e.g., Banks et al., 1997; Barbeito & Simpson, 1991; Sheedy & Fry, 1979), since all such deviations were in the direction of the viewing eye. In the one-eye-closed condition, we think an additional factor is operating: the observers' knowledge of which eye is being used. We elaborate on the role of this knowledge in the General Discussion section of this chapter because a deviation of approximately the same magnitude was found in Experiment 2. The point to be noted now, however, is that the near LED appearing slightly away from the horizontal centre of the nose is not critical to our argument below. What is critical is that the near LEDs *rarely appeared in front of the viewing eye,* contrary to what is expected from Erkelens and van Ee's (2002) claim. According to their claim the LEDs should have appeared directly in front of the viewing eye(s) in all three conditions.

Erkelens and van Ee (2002) assert that Hering (1879/1942) took an irrelevant step when he proposed that the vector defined by a visual target and its retinal image (i.e., the visual axis or visual line) translates to the cyclopean eye. It should be noted, however, that Hering's proposal does not involve a pure translation of vectors as suggested by Erkelens and van Ee. Our finding, which is consistent with Hering's demonstrations, shows that the vectors transfer to the cyclopean eye by rotating about the point at which they intersect the horizontal horopter that includes the intersection of the two visual axes. Examples of this rotation and transference, one for a visual axis and another for a visual line, are depicted in Figure 3.3. The result of this rotation and transference is a "visual direction vector" and is the output of the visual system (a perceptual variable). The visual axes and visual lines, on the other hand, are the "input vectors" (physical variables) and should not be confused with the visual direction vectors. This description of how the visual direction vectors are determined from the inputs from the two eyes applies to both monocular and binocular stimuli and is consistent with van Ee, Banks, and Backus's (1999) recent description.

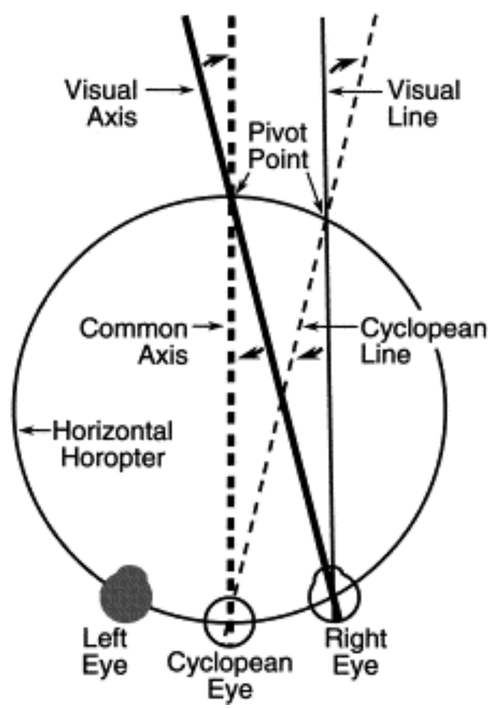

Figure 3.3. An illustration of the rotation of a visual axis and a visual line about the point (labelled pivot point in the figure) at which they intersect with the horizontal horopter containing the intersection of the visual axes. To simplify the figure, the visual axis and the visual line of only the right eye are illustrated. For illustrations of this rotation and transference under binocular conditions, see Figure 1 of Ono and Mapp (1995).

The reported relative visual direction of the near LEDs with respect to the far LEDs was as follows. Both pairs of monocular LEDs (one pair to each eye) were reported to be in the same relative visual direction (i.e., one on top of the other) which is not surprising because each observer adjusted the near LED to appear this way in the pre-experimental procedure. Nonetheless, this result serves the purpose of distinguishing between absolute and relative visual direction. The results clearly show that inferences about absolute direction cannot be based solely upon the observers' reports of relative visual directions.

Our results concerning absolute and relative visual directions demonstrate that the direction of our near LED can be described in at least two ways. It can be described as appearing (a) in the same direction as (or toward the left eye or right eye) the subjective median plane of the head (i.e., in front of the nose), or (b) in the same direction as (or to the left or right of) the far LED. These two descriptions involve different reference axes, namely, (a) the subjective median plane of the head, for absolute direction, or (b) the direction of an arbitrary reference stimulus (the far LED), for relative direction. Asking observers to judge the direction of the near LED with respect to these two reference axes is the operational definition for each of the two types of visual direction. Asking about the absolute direction of the stimulus defines the domain in which the concept of the cyclopean eye is relevant. One of the difficulties in understanding the claim of Erkelens and van Ee (2002) or Erkelens (2000) is that they treat visual direction as a single construct, although a distinction between egocentric (absolute) and allocentric (relative) judgements is mentioned in Erkelens on page 2411. Moreover, Erkelens and van Ee's conclusion that "a reference is *relevant* for motor tasks" but "it is *irrelevant* for visual direction tasks" (p. 1162) may account for the results of Ono et al. (1972) and Ono and Weber (1981) which used a pointing response with an unseen hand, but it fails to explain the results of the present study. There is no action involved with the near LED in this study, yet it appears in front of the nose.

Howard (1982, 1991) identified the sensory information required for each judgment.[4] Relative direction judgments require only information regarding the position of the object's retinal image(s), while absolute direction judgments require both retinal image information and information regarding the position of the eyes in the head. [Logically, an observer could process the absolute directions of two stimuli and derive the relative direction from them. This is not likely, however. See Brenner and Cornelissen (2000) and Sterken, Postma, de Haan, and Dingemans (1999).] Thus, when judging the relative direction of one stimulus with respect to another, be the stimuli monocular, binocular, or a combination of both, information regarding the position of the eyes in the head, or the position of the subjective median plane of the head, is not required. For example, two monocular stimuli with the same horizontal (and different vertical) local sign, or which fall within the Vernier acuity limits of the viewing eye, will appear

[4] What we refer to in this paper as absolute and relative directions were referred to as headcentric and oculocentric directions, respectively by Howard (1982). We chose to use the term "relative", rather than "oculocentric" to avoid the implication that the cyclopean eye is located in an eye. We chose the term "absolute", rather than "headcentric" so as to parallel and contrast the term "relative". The terms, absolute and relative, were also used in Mapp and Ono (1999) for the same reason.

aligned, regardless of eye position.[5] Where the stimuli appear relative to the face (or where the line that passes through the two stimuli appears to point on the observer's face), however, is an entirely separate empirical question.

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[5] This assertion should be limited to two point-like stimuli. Recently, evidence is accumulating that, if monocular stimuli with the same horizontal (and different vertical) local sign are embedded in two different surfaces at different distances, they may not appear to be aligned. See for examples Erkelens and van Ee (1997a, b), Ono (1991), Ono et al. (2000), Popple and Findlay (1998), and Shimono et al. (1998).

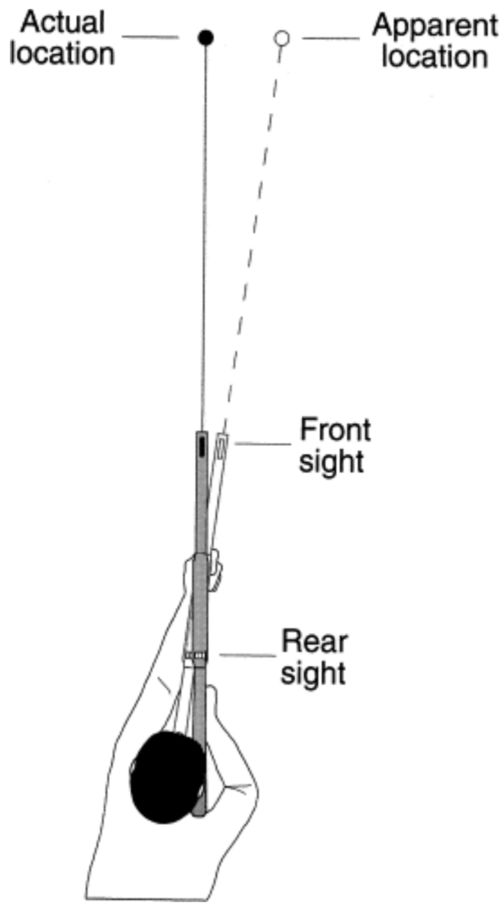

Figure 3.4. The actual and apparent (absolute) visual direction of a target with respect to a rifleman who has monocularly aligned the target, the front sight, and the rear sight. In this task, not only is the concept of the cyclopean eye "irrelevant", so too is the absolute direction of the target. The absolute visual direction of the target is inaccurate, but it does not matter for the question of whether the target is going to be hit or not. The figure is drawn as though the rifleman is esophoric when s/he accommodates to the front sight. If s/he is exophoric, the apparent location of the target would be on the left side of the actual target. If s/he has no phoria and the front sight is accommodated, the absolute visual direction of the target is still inaccurate just as the absolute visual direction of the tree-top and the chimney in Hering's demonstration are inaccurate. The front sight is analogous to the marker on the window pane and the target is analogous to the tree-top or the chimney in Hering's demonstration.

Moreover, Howard's (1982, 1991) analyses together with the results of Experiment 1 define the domains in which the concept of the cyclopean eye is and is not relevant. Clearly, the concept is not relevant for relative direction judgments, since these judgments require only information regarding "the position of the object's retinal image(s)". A rifleman's task is a good case to illustrate the domains. Consider a rifleman trying to align or make collinear a target, the front sight, and the rear sight. For the target to be hit, the absolute visual direction does not matter. What matters is the physical collinearity of the three points, the two sights and the target, which can be attained using a Vernier (relative visual direction) judgement (and consideration of the physical trajectory of the bullet). This does not mean, however, that there is no perceptual consequence. The perceptual consequence is illustrated in Figure 3.4. Also see Figure 3.4 of Ono and Barbeito (1982). Explaining what the rifleman is doing does not require the concept of the cyclopean eye, but explaining the perception illustrated in Figure 3.4 (or what is found in Experiment 1) renders the concept necessary.

Note that in Figure 3.4 (and Figure 3.1) when the two stimuli on a visual line of one eye are physically collinear with respect to that eye, they are perceptually collinear with respect to the midpoint between the eyes. Therefore, the two LEDs at different distances on the visual line of one eye in Experiment 1 cannot both be seen simultaneously in their veridical physical locations as claimed by Erkelens and van Ee (2002) and Erkelens et al. (1996). In our experiment, the near LED, which was physically positioned directly in front of one eye, appeared non-veridically in front of the nose and perceptually collinear with respect to the far LED and the cyclopean eye. This was true for both the bright and the dark conditions. Thus, when describing the results of a visual direction experiment, confusions may arise if the distinction between physical (actual) location and perceptual (apparent) location is not made explicit. See page 1 of Hering (1879/1942) and Mapp and Ono (1999) for an elaboration on this point.

The distinction between physical and perceptual location is also required to describe the empirical finding, of long standing, that what is on a visual axis (or a visual line) appears on the common axis (or a cyclopean line). Although this distinction is mentioned in Erkelens and van Ee (2002), it is not incorporated consistently. Two examples follow:

1. They state that, “Howard and Templeton (1966) and Mitson et al. (1976) would have been forced to conclude that the cyclopean eye is located in the sighting eye if they would have used their visual task in monocular viewing conditions.” (p. 1160). The method involves adjusting a point to appear collinear with respect to another point and the “self”, and Erkelens and van Ee are correct in suggesting that the line passing through the two stimulus points would physically point to the viewing eye. The long-standing empirical finding would tell us, however, that the line would appear to point to the bridge of the nose.

2. In their footnote 3 and Figure 3 they claim that Alhazen’s (1083/1989) demonstration using lines on a board is “misleading” since having “the line point to the pupil of an eye” would lead to view “the two lines as dots”. We are unclear as to what is misleading, but if the lines were to appear as dots they would fuse and would appear on the common axis as shown by Wells (1792) using holes in a sheet of paper that are aligned with the visual axis of each eye. They further state that “the retinal images are vertical lines instead of dots”. If these two retinal images were seen as a (fused) vertical

line in the median plane instead of a line pointing to the nose, then this would not be a compelling demonstration of the fact that stimuli on the visual axes appear on the common axis.[6] That is, the effectiveness of the demonstration depends upon the points on the vertical plane that contains the visual axis appearing at different distances. The seen lines in this demonstration clearly appear to hit you right between the eyes.

Although our Experiment 1 clearly shows that absolute visual direction is referred to the cyclopean eye, it does not provide an answer as to why the cyclopean illusion (Figure 3.1) occurred infrequently in Erkelens's (2000) monocular conditions. As he claims, the prediction from the principles of visual direction that the imaginary line passing through the two stimuli should appear to pivot at the cyclopean eye clearly failed in his monocular condition, except for 33% of his observers in the dark. It must be mentioned, however, that the extent of the cyclopean illusion in binocular and monocular conditions would not be equal unless the common axis, which is yoked to the intersection

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[6] An experimenter dealing with only a single stimulus or stimuli on a given frontal plane need not invoke the concept of the cyclopean eye to describe the actual and perceptual positions of these stimuli. Furthermore, the concept of the direction need not be involved to describe the data: Cartesian coordinates to describe the positions on that plane are sufficient. Therefore, neither of these stimulus situations are ideal for discussions of the usefulness of the concept of the cyclopean eye. Erkelens and van Ee (2002) discussion in their Section 4 deals with these exact stimulus situations (perceptual displacement created with prisms), and the validity of their argument is hard to assess. When the experimenter deals with stimuli at different distances, however, the concept of direction and that of the cyclopean eye become apropos and necessary. We do not address this point further in this paper, except to refer readers to the comprehensive reviews of the topic in the chapter entitled "Adaptation to discordant stimulation" in Howard (1982) and "Adaptation of space perception" in Welch (1986).

of the visual axes, moved through the same extent in *both* conditions. Our explanation of why the cyclopean illusion occurred infrequently in his monocular condition is based on two factors. First, given that accommodation (monocular) drives eye movements less effectively than disparity (binocular) it is unlikely that the common axis moved through as great an extent in his monocular condition as in his binocular condition. Second, it is likely that the presence of a stable background and the lack of change in the relative direction of his two stimuli “overrode” the small change in absolute direction. We discuss the second factor in the General Discussion section of this chapter in reference to the results of his Experiment 3.

Our argument that the common axis moved through a lesser extent in Erkelens's (2000) monocular condition than in his binocular condition is based on the following findings. Ono and Gonda (1978) and Ono and Weber (1981), found that absolute direction seen with one eye can be explained by the deviation of the common axis from the stimulus, namely, phoria. [Phoria is defined as “The direction or orientation of one eye, …in relation to the other eye, manifested in the absence of an adequate fusion stimulus…” (Cline, Hofstetter, & Griffin, 1989, p. 529). See Figure 3.5 for an illustration of phoria.] Others have found that the magnitude of phoria, with respect to the fixation point, increases with closer fixation (Barbeito & Simpson, 1991; Holland, 1958; Ono & Weber, 1981). If one thinks of phoria as a mismatch between accommodation and vergence angle, then our argument can be understood by considering the effectiveness of accommodation in an accommodative vergence situation. First, consider the case in which accommodation is completely ineffective, such as when the stimuli are closer than the eye’s near point of accommodation. In this case, the occluded eye would drift to the physiological resting state (for a discussion, see e.g., Owens & Tyrrell, 1992), and would remain there. Second, consider the case in which accommodation is effective but the coupling between accommodation and vergence is not perfect, and in which exophoria is larger when the stimulus is closer. Such a case is illustrated in Figure 3.5 in which Panel A shows larger exophoria than Panel B. In this case, the common axis would move through a lesser extent than in a binocular condition. Finally, consider the case in which accommodation is effective and the coupling between accommodation and vergence is perfect. In this case, the occluded eye would move in accordance with the change in accommodation, and the common axis would move through the same extent as in a binocular condition.

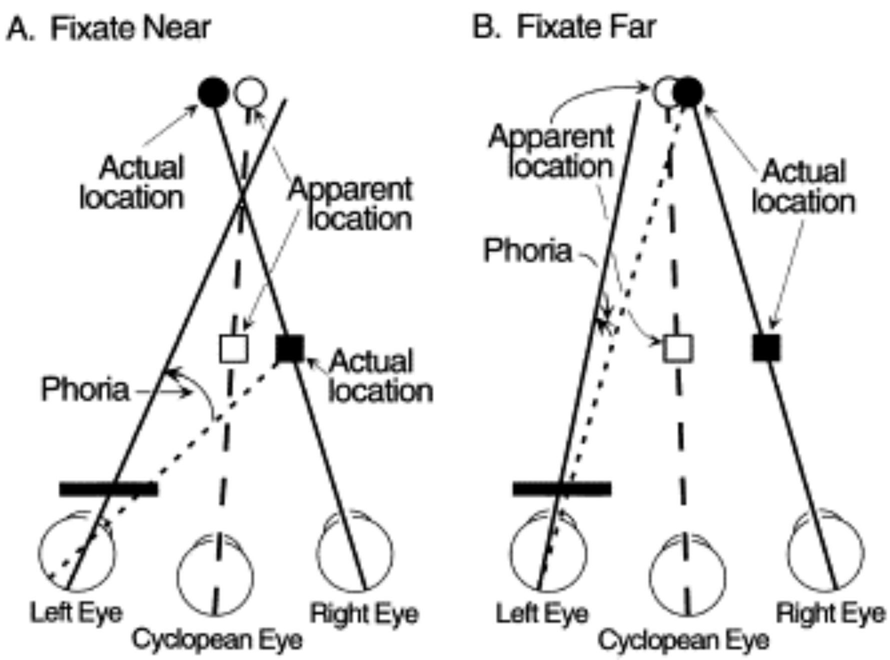

Figure 3.5. Illustration of the apparent locations of stimuli on the visual axis of the right eye as a result of exophoria. The phoria is indicated by the angle between the visual line to the stimulus (dotted line) and the visual axis of the left eye. When fixation changes from the near stimulus (Panel A) to the far stimulus (Panel B) the absolute visual direction of the far stimulus shifts to the left. The two stimuli on the visual axis of the right eye are seen on the common axis (dashed lines) as in Figure 3.1, but the motion of the common axis as a function of the change in fixation is smaller.

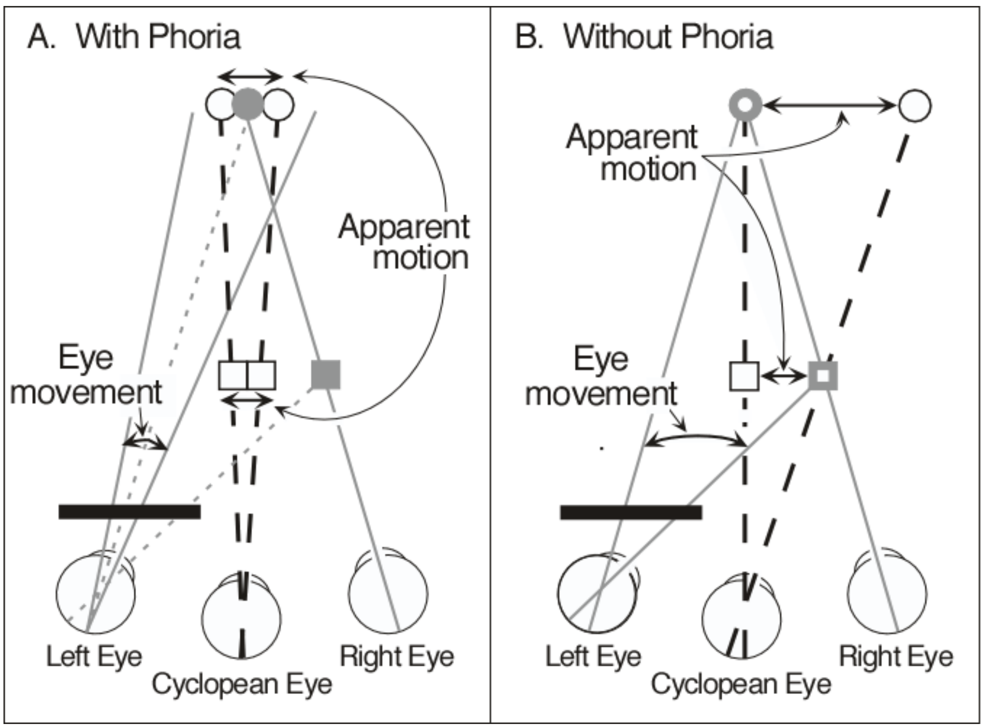

Figure 3.6. Illustration of a reduction in the extent of the cyclopean illusion as a result of phoria. The extent of the apparent motion of the common axis with phoria (Panel A) is derived from the two fixation conditions shown in Figure 3.5. The extent of the apparent motion of the common axis without phoria (Panel B) is derived from the two fixation conditions shown in Figure 3.1. The extent of apparent motion is smaller with phoria than without.

From the different extents of eye movements (and common axis movement) described in the three monocular situations above we predict different extents of the cyclopean illusion. No illusion is predicted for the condition in which accommodation is ineffective, because the common axis does not move. The extent of the illusion for the condition in which accommodation is partially effective is illustrated in Panel A of Figure 3.6. The extent of the illusion predicted in the condition in which there is no phoria is illustrated in Panel B of Figure 3.6. (The extent of the illusion in Panel A is derived from what is illustrated in Figure 3.1.) Note that the extent of the illusion is smaller in Panel A, which depicts the usual monocular condition, than in Panel B, which depicts the unusual monocular condition in which the extent of the eye movement is the same as it would be in a binocular condition. Phoria also accounts for the two informal observations reported by Erkelens (2000). His Observation 1 (page 2412-2413), that a bead moving toward the eye along the visual axis appears "as a pure approach without any change in direction", can be explained by the phoria increasing as the bead approaches. Furthermore, the first part of his Observation 2 (page 2413) that there is an apparent shift in the absolute direction of a stimulus positioned straight-ahead of the nose, when binocular viewing is switched to monocular viewing, can also be explained by the phoria that takes place. Moreover, his observation that the magnitude of this apparent shift increases as the viewing distance decreases is completely consistent with the phoria literature — namely, the smaller the viewing distance the greater the exophoria. In the second part of Observation 2, Erkelens noted that there is no such apparent shift, when a portion of the stimulus on the same sheet of paper is occluded. This can be explained by a lack of phoria, because phoria does not occur when a binocular stimulus is present. Irrespective of whether phoria occurs or not, his Observation 2 does not provide any evidence in support of his claim that “perceived direction during monocular viewing is based on the signals of the viewing eye only" (p. 2411). If anything, this observation contradicts his claim. That is, when one closes one eye in this situation the open eye remains directed at the target and the image of the target remains on the fovea. Therefore, if the visual system were to switch from monitoring the signals of both eyes to monitoring the signals of the viewing eye only there would be no shift in the absolute direction of the target. Moreover, even if the open eye were to move, the movement of the eye would be accompanied by an equal and opposite shift in the angular position of the target’s retinal image, and again there would be no shift in the absolute direction of the target. In any event, his Observations 1 and 2 do not constitute grounds to dismiss, as he has done, the previously published reports about the monocular cyclopean illusion that he cites (i.e., Ono et al., 1972; Ono & Gonda, 1978; Ono & Weber, 1981; Park & Shebilske, 1991).

Experiment 2

Before introducing Experiment 2, we comment on the eye movement traces (p. 2416) in Erkelens's (2000) binocular and monocular conditions. We disagree with Erkelens’s claim that the eye movements in the two conditions are essentially the same. Our inspection of his Figure 3 indicates that (a) both the “tracking” and “stepping” eye movements in his monocular conditions are smaller than in their respective binocular conditions, which is consistent with the idea that the closer the stimulus the greater the phoria, and (b) the "stepping" eye movements in his monocular condition are slower than in the binocular condition (i.e., the destination is reached by a slow asymmetrical vergence in his monocular condition, whereas it is reached by fast binocular saccades in his binocular condition). The conclusion from our inspection of his tracking data is consistent with Erkelens and Regan's (1986) finding that a monocular stimulus is considerably less effective at driving an eye movement than is a binocular stimulus. Moreover, the conclusion from our inspection of his stepping data is consistent with the literature pertaining to accommodative vergence eye movements in response to a stepped stimulus (e.g., Alpern & Ellen, 1956; Cumming & Judge, 1986; Enright, 1992; Hermann & Samson, 1967; Keller & Robinson, 1972; Kenyon, Ciuffreda, & Stark, 1978; Ono & Nakamizo, 1978; Saida, Ono, & Mapp, 2001) and with reports about binocular fixation changes between stimuli on a visual axis (e.g., Alpern & Ellen, 1956; Ono & Nakamizo, 1977, 1978; Ono, Nakamizo, & Steinbach, 1978; Riggs & Niehl, 1960; Westheimer & Mitchell, 1956; Yarbus, 1967). The differences we note between Erkelens's monocular and binocular conditions are well documented in these references. Therefore, it is very likely that the smaller and slower eye movements in his monocular conditions contributed to his observers not experiencing the cyclopean illusion. Moreover, individual differences in the magnitude and the angular velocity of eye movements may account for why 33% of his observers did experience the cyclopean illusion in the dark.

Experiment 2 had four parts. In part (a) we measured the relative visual direction of monocularly presented stimuli comparable to those used by Erkelens (2000) with respect to the absolute direction of the near LED used in Experiment 1. In part (b) we determined the number of observers who experience the cyclopean illusion. In part (c) we measured the phoria associated with the stimuli. In part (d) we measured and analysed the eye movements of several observers. Comparable to Erkelens's tracking condition, our observers tracked a stimulus that moved back and forth on the visual axis of one eye;

comparable to his stepping condition, our observers changed fixation between two stationary stimuli positioned on the visual axis of one eye. For (a) and (b) we presented these two conditions with the near LEDs used in Experiment 1. For (c), we measured phoria at the end of the experiment, and for (d), we asked several observers to return to have their eye movements recorded.

Methods

Observers

The observers who served in Experiment 1 participated in parts (a) to (c) of Experiment 2. There was a rest period of approximately 10 minutes between the two experiments. Four observers from the original 12 participated in the portion of the experiment to measure eye movements. Two of them had reported the cyclopean illusion and two had not. The eye movement recording sessions took place three or four weeks later.

Stimuli and Apparatus

Two additional LEDs (Chicago Miniature IDI 5370T7) which emitted yellow light instead of green light replaced the far LEDs in the apparatus used in Experiment 1. They were mounted on a moveable track such that they could be aligned with the right eye and also to the near (green) LED used for the right eye in Experiment 1. The biteboard and the near LED were positioned as in Experiment 1. Phoria was measured by placing a variable dioptre prism, with a range of +/-30 dioptres and Maddox rods, in front of the left eye. The measurement involved adjusting the variable dioptre prism until the image of a light source that appeared as a vertical line of light (produced by the Maddox rod over the left eye) appeared superimposed on the light source seen from the right eye. The extent of the adjustment defined the phoria.

The eye-movement recording sessions were conducted in a different room, and the near LED was removed because it interfered with the eye movement recording system. Except for this, the stimulus configuration was the same and the moving LED was moved with an MFE (Model No. 835M) X-Y Plotter, instead of having it moved manually by the experimenter. Horizontal eye movements of both eyes were recorded with the El-Mar Series 2020 binocular CCD video-based eye-tracker, which has high resolution and compares favourably to the magnetic search coil technique (DiScenna, Das, Zivotofsky, Seidman, & Leigh, 1995). The system has a maximum resolution of 6 minutes of arc, a 120Hz sampling rate and a linear range of +/-30 and +/-25 degrees, in the horizontal and vertical meridia, respectively. The horizontal positions of the left and right eyes were averaged ((left + right)/2) and all analyses were performed on these averaged eye position data. A rationale for the averaging procedure is presented in the Results and Discussion section below.

Procedure

The basic experimental design for parts (a) and (b) consisted of the two eye-movement conditions mentioned above. In the tracking condition, the experimenter moved the closer yellow LED back and forth 10 times through a 13 cm extent from 15 cm to 28 cm as smoothly as possible with a cycle of 3 seconds. A metronome set to sound every 1.5 seconds was used to synchronize the movements. (Before each experimental session, the experimenter practiced moving the LED.) In the stepping condition, observers were instructed to alternately change their fixation 10 times between the two yellow LEDs (at their own pace). One LED was 15 cm and other was 30 cm in front of the observer's eye. An eye patch was placed over the left eye. For half of the 12 observers the tracking condition preceded the stepping condition, and for the other half the stepping condition preceded the tracking condition.

After each stimulus presentation, observers were asked three questions: (a) To which part of your face did the imaginary line, connecting all three lights, appear to point? (b) As you tracked the near yellow light or as you changed fixation between the two yellow lights did the imaginary line appear to shift? If so, how? (c) Relative to your face, where did you see the green light? (i.e., in front of your nose, in front of your eye, or in-between your nose and your eye). After reporting their percepts, they were asked to close their eyes while the stimulus was adjusted for the next condition.

Following the two stimulus presentations, phoria was measured for the two LEDs that were 15 cm and 30cm away from the observer (as in the stepping condition). There were three measurements for each distance. In the eye-movement session, before data collection for each observer began, the recording system was calibrated by having binocular fixations at seven vertical and seven horizontal points across a range of +/- 10 deg at a distance of 2 m from a calibration array projected onto a screen.

Eye movements were recorded for binocular as well as monocular conditions in the bright and dark room conditions. The eye-movement recording portion of the experiment had eight conditions (2 x 2 x 2), namely, tracking and stepping X binocular and monocular X bright and dark room illumination conditions. Within each of these conditions we recorded the observer's eye movements for a period of one minute. In the tracking condition this represented 20 cycles and in the stepping condition (which was self–paced) it represented 10 to 23 cycles. The “binocular” refers to the near stimulus being binocular but not the far one (see Figure 3.1). For the monocular condition, an occluder was positioned behind the camera for the left eye.

Results and Discussion

Most observers reported that the imaginary line connecting the three LEDs pointed to the nose or near it, and that the near one appeared in front of or near the nose. However, the two reports were not always consistent. One observer reported that the line pointed to the right eye in both the tracking and stepping conditions, but reported that the near LED appeared near the nose in the tracking condition and near the eye in the stepping condition. This observer was the one who reported that the near LED appeared in front of an eye in Experiment 1. We performed the same analysis as in Experiment 1 to summarize where on the face the line appeared to point or where the near LED appeared with respect to the face (i.e., the absolute direction). The means and (standard deviations) were 1.13 (1.11) in the tracking condition, and 1.17 (1.25) in the stepping condition. The numerical values are close to those obtained in the one eye closed condition in Experiment 1 and are discussed in the General Discussion section of this chapter. Note that, except for the one observer reported above, both the stationary and the moving LEDs were referred to the cyclopean eye. Therefore, the rarity of the monocular cyclopean illusion noted by Erkelens (2000) is not a consequence of the directions of the LEDs being referred to the viewing eye.

Four observers reported apparent movement of the imaginary line, but only two reported what we would consider to be the cyclopean illusion. Observer LT reported that the line pivoted very near the face and the far stimulus moved about 1.5 cm in both the tracking and the stepping conditions. Observer YL reported the same perception but only in the tracking condition. Observer CL reported that the line pivoted very slightly at the far LED and the near green one appeared to move slightly in the tracking condition; TR reported the same in the stepping condition. We have no good explanation for this report, except to speculate that the procedure for aligning the three LEDs was inadequate for these two observers.

Table 3.2. Phoria in dioptres for two distances for each observer and the occurrence of the cyclopean illusion in Experiment 2. Positive values represent exophoria and negative values esophoria.

Observers	**15 cm**	**30 cm**	**Illusion**
RK	30+	9.0	no
LT	5.13	0.88	yes
NT	21.00	-11.67	no
LL	30+	7.33	no
PG*	8.60	-5.00	no
CA	27.25	7.00	no
CL	30+	11.00	no
DH	27.33	4.67	no
MK	30+	10.00	no
YL	30+	2.67	yes**
DT	30+	12.00	no
TR	30+	18.67	no
Mean	?	5.55	
S.D.	?	8.08	

*PG was able to superimpose the LED and the apparent line by changing his vergence. His phoria values were obtained by asking him to view the stimuli "passively".

**in one condition

The means of the phoria in dioptres for each observer are shown in Table 3.2. (One prism dioptre corresponds to a 1 cm displacement of the light at a distance of 1m.) Also, the two observers who experienced the cyclopean illusion are identified in the table. For all 12 observers, the phoria at 15 cm was considerably larger than at 30 cm. Indeed, for seven observers, the phoria at 15 cm was larger than we could measure with the +/-30 dioptre variable prism. The very large phoria associated with the near LED (15 cm) indicates that, when fixating at this distance in either the tracking or the stepping condition, the visual axes intersected at a point far beyond the stimulus. Given that this was likely the case in Erkelens's (2000) study, the extent of the eye movements in his monocular condition would be much smaller than in his binocular condition. Note that the two observers who experienced the cyclopean illusion had the smallest phoria for the stimulus at 30 cm. The results shown in Table 3.2 strongly suggest that the weaker oculomotor signal was a contributing factor in the low frequency of seeing the cyclopean illusion in the monocular condition.

There is, however, another logically feasible way to describe this weakness. All eye movements, including those in which one eye remains stationary, can be formally analysed in two ways. One way is to analyse the magnitude, direction, and velocity of each eye separately, another is to analyse the coordinated movements of both eyes together, in terms of the version and vergence components. Version is a coordinated eye movement in which the rotations of the two eyes are equal in magnitude and direction. Vergence is a coordinated eye movement in which the rotations of the two eyes are equal in magnitude but opposite in direction. The eye movements required to track, or alternately fixate, stimuli on the visual axis of one eye, such as in the present experiment, include both version and vergence components. The relevant component for absolute visual direction and the cyclopean illusion is version, because it is the component that specifies the magnitude, direction, and velocity of horizontal common axis motion resulting from the coordinated horizontal movements of the two eyes. In the analyses to follow, we compared the magnitudes and the peak angular velocities of the version component in the monocular conditions to those in the binocular conditions. For all analyses, the version component was computed by averaging the horizontal positions of the left and right eyes ((left + right)/2). (For a more comprehensive discussion of the combination of version and vergence, see Ono, 1980, 1983; Howard, 1982.) In this experiment, the predicted magnitude of the version component, when there is no phoria or fixation disparity, is 5.33 degrees in the tracking condition (the stimulus moved only to 28 cm), and 5.76 degrees in the stepping condition. (These magnitudes were calculated using the value of 6.2 cm for the interocular distance.) A larger version component than the predicted value is expected in the binocular stepping condition because, in this condition, the far stimulus was monocular and, therefore, when the observer attempts to fixate it the visual axes would intersect beyond and to the left of the stimulus due to exophoria.

The mean magnitudes of the version component of the eye movements in both the tracking and the stepping condition, and the mean peak angular velocities in the stepping condition are shown in Figure 3.7. The mean values for the stepping conditions are based on the data from three observers only. Observer YL's eyes did not move in the two stepping conditions. See appendix for her sample eye movements. The figure shows two striking differences that are not reported in Erkelens (2000): (a) the version component of the eye movements in the monocular condition was much smaller and slower than in the binocular condition, and (b) within the monocular condition, the version component of the eye movements in the dark condition was smaller and slower than in the bright condition. The difference described above in (b) suggests that in the bright condition an isotropic rate of change in retinal image size of the stimulus holder served as a cue for a change in the distance (e.g., for perception, see Ittelson, 1951; Regan & Beverley, 1978; Gray & Regan, 1998; for eye movement, see Erkelens & Regan, 1986), and that in the dark condition a small LED as a fixation point is a poor stimulus for accommodation (Aggarwala, Nowbotsing, & Kruger, 1995; Owens & Leibowitz, 1975). In the appendix, we show sample version traces of all four observers, and the mean magnitudes (standard deviations) of the version component of the eye movements for each sub-condition.

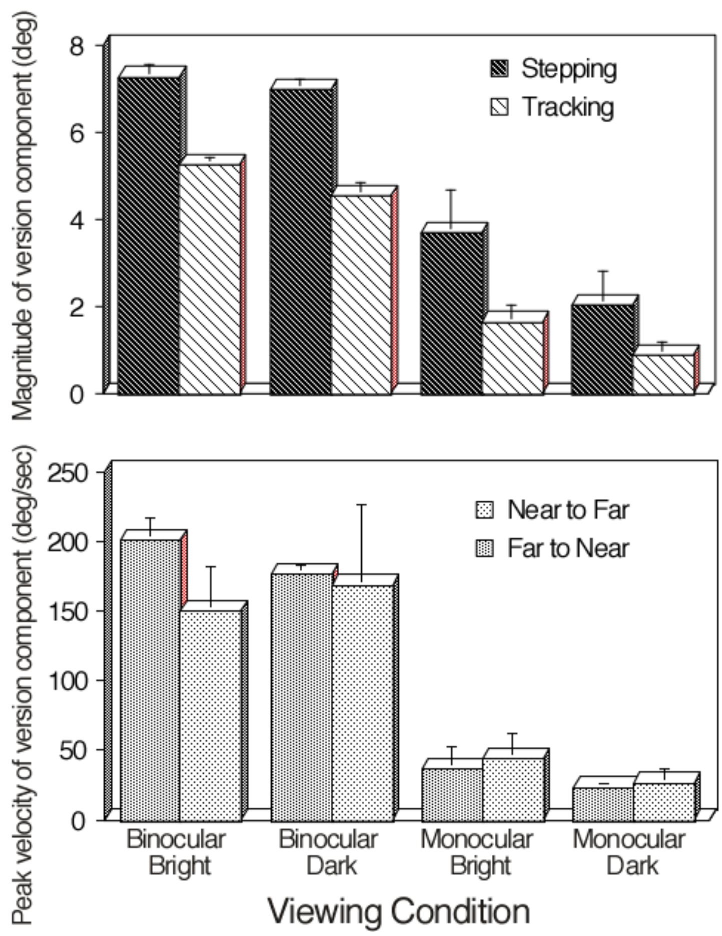

Figure 3.7. Mean magnitudes and peak angular velocities of the version component of the eye movements from the four observers who participated in the eye movement monitoring session in Experiment 2. The version component was computed by averaging the horizontal positions of the left and right eyes ((left + right)/2). The upper panel shows the mean magnitude and standard error in the tracking and stepping conditions. The lower panel shows the mean peak angular velocity (absolute values) and standard error of the near-to-far and far-to-near eye movements in the stepping condition. (n = 4 in the tracking condition; n = 3 in the stepping condition.)

The mean magnitudes and the mean peak angular velocities of the version component of the eye movements shown in Figure 3.7 clearly contradict Erkelens's (2000) interpretation of his data that, "In general, the amplitudes and the speeds of the eye movements were similar in binocular and monocular viewing conditions." (p. 2415). Our data show that the monocular condition produces smaller and slower eye movements than the binocular condition. Moreover, we think his data do, too, if he were to analyse them as we did ours. Our finding is consistent with the tracking eye movement data reported in Erkelens and Regan (1986) and with the stepping eye movement data reported in the literature cited in the preamble of this section. Thus, our finding and the literature cast into doubt Erkelens's assertion that, "The important conclusion from this result is that eye movements do not explain the absence of the cyclopean illusion during monocular viewing (p. 2415)". The smaller and slower eye movements, and the consequential smaller and slower movements of the common axis, partly account for why only a small number of observers experienced the cyclopean illusion in his and our monocular conditions. The data also show, however, that the eye movements or lack thereof are not the sole determining factor. This is so, because the monocular eye movements in the bright condition were larger than in the dark condition, yet none of the observers experienced the illusion in the bright condition in Erkelens's study. Another contributing factor is discussed in the next section with reference to his finding that, "None experienced the illusion during monocular viewing of monocular targets against a large background (p. 2416)". We speculate that this finding is due to the relative visual direction of a monocular target with respect to a stable background remaining the same despite a movement of the non-viewing eye.

This speculation indicates that Erkelens and van Ee's (2002) assertion that "the argument that the two eyes always act as a single sensor was recently falsified by experiments … (Erkelens, 2000)" (p. 1158) is at best premature. Moreover, their generalization that the cyclopean illusion does not occur "…during monocular viewing of full-field scenes in daylight conditions" may also be premature. First, the literature, without specifying the requirement of darkness, documents the existence of the illusion under monocular viewing conditions [e.g., Enright (1988, p. 925), Helmholtz (1910/1962, p. 253), Hering (1879/1942, p. 42), and Carpenter (1988, p. 308-309)]. This suggests to us that the illusion is likely to occur in a daylight condition without a background (or with a background that does not provide any information about the relative direction of the target). Second, the phoria results of our experiment indicate that having the two accommodative stimuli very close to the face is not conducive to producing the illusion. Thus, unlike the stimulus arrangements chosen by other researchers, the particular arrangement used by Erkelens was one for which it is particularly difficult to produce a monocular cyclopean illusion.[7]

Since these possibly premature generalizations are the basis of the arguments in Erkelens (2000) and Erkelens and van Ee (2002), their arguments are not persuasive. The traditional view that the two eyes work as one organ (Hering, 1868/1977) is more

[7] We are now planning experiments to determine the necessary conditions for the monocular cyclopean illusion. In a pilot study, we changed the distance of the stimulus and asked observers from Experiment 2 that did not see the illusion to come back. Most of these observers now experience the illusion. In these experiments, we will test Erkelens (2000) hypothesis that when one closes one eye the resultant difference in luminance between the two eyes causes the signals of the closed eye to be suppressed.

parsimonious than Erkelens's, in that no new mechanism is required. His idea requires that the visual system monitor the signals of the viewing eye only, when the stimulus is seen monocularly in the light and sometimes in the dark, and then switches to monitoring the signals of both eyes when there is a binocular stimulus. We find it difficult to imagine the advantage of his proposed mechanism or what kind of evolutionary pressure would create it, particularly because a monocular stimulus is not referred to the viewing eye as indicated in the literature and as we found in Experiment 1.

General Discussion

In our discussions of Experiments 1 and 2, we did not make a distinction between visual and motor reference points as did Erkelens and van Ee (2002). We have treated the two terms as synonyms and also as being synonymous with other terms such as binoculus, centre of visual direction, and projection centre. However, when clear operational definitions to distinguish between visual and motor reference points are provided, the distinction between them may eventually provide a better understanding of how the visual system processes direction. (For a discussion of operational definition see e.g., Bridgman, 1927; Feigl, 1945; Green, 1992; Stevens, 1935). Detailed experimental procedures to measure the construct are needed, as we have done for the distinction between absolute and relative direction in Experiment 1. Moreover, the motor reference point they propose, must also be operationally distinguished from the kinaesthetic-tactile reference centre discussed in Howard and Templeton (1966). The different methods (see e.g., Barbeito & Ono, 1979; Howard & Rogers, 1995) that have been used to measure the visual centre may indeed be measuring different points that should be explained by different constructs, since reference points measured with different methods do not correlate across different observers (Mitson et al., 1976). None of the methods, however, indicate that the centre is located in one eye as required by Erkelens et al.'s (1996) proposal, and the lack of correlation among different methods may be due to the lack of precision of these methods. In working towards better operational definitions of whatever construct may emerge to explain visual direction, the points made below must be incorporated.

Although the assumption in visual direction research is that absolute or relative direction is processed independently of depth or distance, the distance of the stimulus is an important experimental variable. For a very distant stimulus, visual direction referred to the cyclopean eye becomes experimentally indistinguishable from that referred to one eye. Our presenting the near stimuli very close to the eye(s) in Experiments 1 and 2 allowed us to make inferences about absolute direction. Erkelens's (2000) presentation of the accommodative stimuli too close to the face led to a low frequency of observers experiencing the cyclopean illusion.

There is another subtle but important experimental variable that was not controlled for in either our study or Erkelens (2000), namely, the observers' knowledge of (a) where the stimuli are with respect to their face, (b) which eye is being used, and (c) where each eye is located in their head. If observers were to base their judgement solely on this knowledge, they would have to report that the near stimulus is in front of the viewing eye. Moreover, there can be a subjective impression that we are seeing with and from the viewing eye, analogous to the impression that observers get when performing an utrocular-discrimination task (for discussions, see e.g., Blake & Cormack, 1979; Ono & Barbeito, 1985; Steinbach, Howard, & Ono, 1985). For example, dropping an eye drop into an eye does not give an impression of dropping it on the bridge of the nose, nor does looking through a tube or a single view microscope give a compelling impression that we are seeing as though from the bridge of the nose.[8] The point being made is that the subjective impression that one is seeing from one eye is likely based on the knowledge listed above and is not necessarily counter evidence for the idea that we see as though from a cyclopean eye. An analogy is that the subjective impression of seeing with a particular eye does not indicate that one can make such a discrimination under controlled experimental conditions. We speculate that the knowledge listed above affected the observers' reports. The subjective impression that we are seeing from one eye is likely to have contributed to the report made by one observer in the one-eye-closed condition in Experiment 1, and in Experiment 2 in which an eye patch was used. In both experiments, he asked during the pre-experimental procedures whether to align the stimulus to an eye when we instructed him to move the stimulus to appear above or below another one. That is, he had the knowledge that the stimuli were being aligned to an eye. We further speculate that this knowledge played a role in the claims that the cyclopean eye moves to the viewing eye (Erkelens et al., 1996), that only the signals from the viewing eye are

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[8] Placing an index finger in front of an eye also does not lead to a perception that the finger is in front of the nose. Ono and Angus (1974) considered this stimulus situation as producing a conflict between the absolute visual direction and the felt position of the finger and performed an adaptation experiment. When the finger is repeatedly placed and removed from in front of the eye, the felt position of the finger changed in the direction of the nose as indicated by open-loop pointing to that finger with the index finger of the non-adapted hand.

monitored (Erkelens, 2000), and that the cyclopean eye is always irrelevant (Erkelens & van Ee, 2002).

There is nothing in our results or in the literature that supports Erkelens and van Ee's (2002) claim that the cyclopean eye is always irrelevant, or Erkelens's (2000) conclusion in his last paragraph that what is stated in Ono (1991) "is not correct." This is not to say, however, that the laws of visual direction as summarized in Ono (1991), in Ono and Mapp (1995), or in Howard and Rogers (1995) are complete enough to account for visual direction in all stimulus conditions. One thing that is missing is consideration of the background. For example, there is no provision in the laws to incorporate the Duncker effect (1929/1935) or induced movement (see e.g., Howard, 1991; Wade & Swanston, 1987). While fixating on a stationary dot surrounded by a moving background, the dot appears to move in the direction opposite the background and the background tends to appear stationary. This phenomenon is an example of what cannot be explained by the existing laws of visual direction. A more striking violation of the laws is the phenomenon in which an after-image of an entire room remains perceptually stationary even when the observer makes an active eye movement (Davies, 1973; Pelz & Hayhoe, 1995; Swindle, 1916; Zenkin & Petrov, 1979). These phenomena suggest to us that information about the relative direction of a stimulus, with respect to the background, can "override" the information about absolute direction information from the oculomotor signals and the retinal signals. The results of Erkelens's Experiment 3 reflect how large the background had to be before it had its effect on his four observers who experienced the cyclopean illusion (rather than how large the difference in luminance to the two eyes had to be). Moreover, the lack of the illusion in daylight in his monocular conditions can be attributed to the background remaining perceptually stationary, and to there being no change in the relative direction of the two stimuli or the moving stimulus, relative to the background in his Experiments 2 and 3.

The foregoing discussion also suggests that the visual system is more sensitive (indicated by a lower discrimination threshold) to relative direction than to absolute direction. "Hyperacuities" such as Vernier acuity are in the seconds of arc range, whereas the standard deviation of setting a stimulus at 25 cm or 50 cm to the subjective median plane is over 2 degrees within and between observers (Ono & Weber, 1981). Moreover, when we attempted to measure the subjective straight-ahead by having observers set the position of a binocularly viewed single light 2 m away in the dark in a pilot study, we found that some observers did not see the movement of the light, even though the same movement was easily seen when the room lights were on in Ono, Tam, and McConnell (1983). The high precision for relative direction judgements and low precision for absolute direction judgements are consistent with the general psychophysical fact that relative judgments are more precise than absolute judgements. For example, a common or absolute motion is more difficult to detect than relative motion (e.g., Leibowitz, 1955; Snowden, 1992), and a change in absolute disparity is more difficult to detect than a change in relative disparity (e.g., Erkelens & Collewijn, 1985; Gogel, 1965; Regan, Erkelens, & Collewijn, 1986). Therefore, the difficulty in judging the absolute direction of a stimulus far away from the face is not an isolated perceptual phenomenon.

Given the high sensitivity to relative direction, the visual system can provide precise information about where an object is located with respect to its background or with respect to another stimulus. This information is useful when elements in the background or the other stimulus are already localized. Although the processed absolute direction may be imprecise when compared to relative direction, the absolute direction of a stimulus in the manual work space is necessary for action (e.g., reaching response). This speculation may come close to what underlies Erkelens and van Ee's (2002) idea that the cyclopean eye is for action and irrelevant for visual direction, if by visual direction they mean relative visual direction.

Finally, to understand better the concept of the cyclopean eye, a point sometimes made but not emphasized (see Ono, 1979) is noted here to conclude this paper. The cyclopean illusion and the time-honoured demonstrations listed in Experiment 1 require the concept of the cyclopean eye to explain them. When these observations are summarized as "Objects situated in the Optic Axis *(i.e., Visual Axis)*, do not appear to be in that Line, but in the Common Axis" (Wells, 1792, p. 46; italics ours), however, the implication of how the visual system and the oculomotor system work together to process direction from the cyclopean eye is not made explicit. Whenever the two eyes move to an object of interest, the common axis moves. This movement brings the common axis to pass through the object and the object is seen in the correct direction from the cyclopean eye. The illusion of seeing another object on the visual axis in an incorrect location is an epi-phenomenon for the two systems, oculomotor and visual, that evolved together to process correctly the direction of a binocularly fixated object. It is reasonable to conjecture that the two systems did not evolve to allow us to locate non-fixated stimuli or to make a line that points to an eye appear to point to the bridge of the nose. This epi-phenomenon, however, indicates to visual scientists that a binocularly or monocularly viewed object is seen from the cyclopean eye, and that the retinal location(s) of the stimulus and the joint eye positions together determine the absolute visual direction. The illusion that continues to hit you right between the eyes is a good example of the adage that "Illusions of the senses tell us the truth about perception."— "das Sinnestäuschungen Gesichtwahrheiten sind." (A quote attributed to Purkinje by Teuber, 1960, p. 1602).

Addendum

In response to Erkelens and van Ee's (2002) addendum, we reiterate and briefly elaborate on a few key points made in our paper. In the spirit suggested by the action editor, R. Blake, we offer constructive suggestions as to how to resolve the outstanding issues.

For Experiment 1, the empirical question remains as follows: Where do observers perceive stimuli physically positioned on the visual axis of one eye, when the other eye is occluded? Do the stimuli appear in their veridical locations (i.e., on the visual axis), as claimed by Erkelens (2000) and Erkelens and van Ee (2002) or do they appear in illusory locations (i.e., on the common axis) as claimed by us? Our results complimented what has been reported in the literature for over two millennia; namely, the stimuli appeared on the common axis. Since the question involves the perceived locations of the stimuli rather than the observers' knowledge of the physical locations of the stimuli, observers were asked to report their percept. Erkelens and van Ee suggest that this procedure does not meet today's psychophysical standards. We had assumed, reasonably we think, that the known location conflicted with the perceived location. An alternative procedure would be to prevent observers from having any access to information about the stimuli's actual locations. In the spirit of trying to resolve this issue to their satisfaction, we are willing to design and conduct such an experiment with them; we are confident that our results will be confirmed. Moreover, their concern about observers coming off the bite-board to make their responses is not germane to the empirical question. The question is concerned with the accuracy (constant error) of the reports, not the precision (variable error). Thus, a case cannot be made that "a translation of the head of ± 1 mm" caused the stimuli to be perceived on the common axis (in front of the nose) instead of on the visual axis (in front of the eye). Also, any translation of the head upon returning to the bite-board would have resulted in a shift in the relative direction of the stimuli; no such shift was reported by any of our 12 observers.

For Experiment 2, their critique is based on an incorrect assumption. We did not argue, as they suggest, that the sole determinant of the cyclopean illusion is the magnitude of the eye movement. We hypothesized that information about the relative direction of the stimuli with respect to the background can, in certain stimulus situations, "override" information about absolute direction, and thus affect the occurrence of the illusion. Without this hypothesis Erkelens (2000) himself cannot account for the results of the four observers who experienced the illusion under his monocular viewing condition. His results falsify ("one would have sufficed" to use Erkelens and van Ee's [2002] term) his hypothesis that perceived direction during monocular viewing is based on signals from only one eye. Moreover, the imaginary line that points to the nose and "pivots" very near or at the face is a description of the cyclopean illusion. See Figure 3.1. Erkelens and van Ee attribute this pivoting to a "misalignment between the stimuli and the viewing eye". If, as they argue, perceived direction during monocular viewing is based on signals of the viewing eye only, then no such pivoting (change in absolute direction) should occur. This holds true irrespective of whether the stimuli are aligned or not. The only way such pivoting can occur is if the signals of both eyes are used. In any event, in the spirit of resolving this issue, we are willing to share with them, or any other interested readers, the eye movement data from our observers' individual eyes.

Finally, we note that no explicit distinction between relative and absolute direction was made in either Wells (1792), in Hering (1879/1942), or in what Ono and Mapp (1995) called Wells-Hering's laws of visual direction. We now have a schematic input-output representation of a direction mechanism that combines Wells and Hering's thinking and this important distinction. Readers are referred to Ono, Lillakas, and Mapp (2003) to examine this combination as well as a further discussion on the relevance of the concept of the cyclopean eye.

Appendix

We present sample version traces of four observers in Figure 3.8, and the mean magnitudes of each sub-condition for each observer in Table 3.3. (The mean peak velocities were not included to shorten the appendix.) The traces reported in Figure 3.8 are meant to supplement those shown in Erkelens (2000) and include traces he did not report (i.e., those from the dark condition). These traces mirror what is reported in Table 3.3. The traces and mean values show that the version eye movements, in both the tracking and stepping conditions, were smaller with monocular viewing than with binocular viewing. They also show the differences between the bright and dark conditions: the dark condition produced smaller version eye movements than the bright condition. However, the association between whom experienced the cyclopean illusion and the magnitude of the eye movement in the monocular dark condition was not perfect. Comments on the individual eye movements follow.

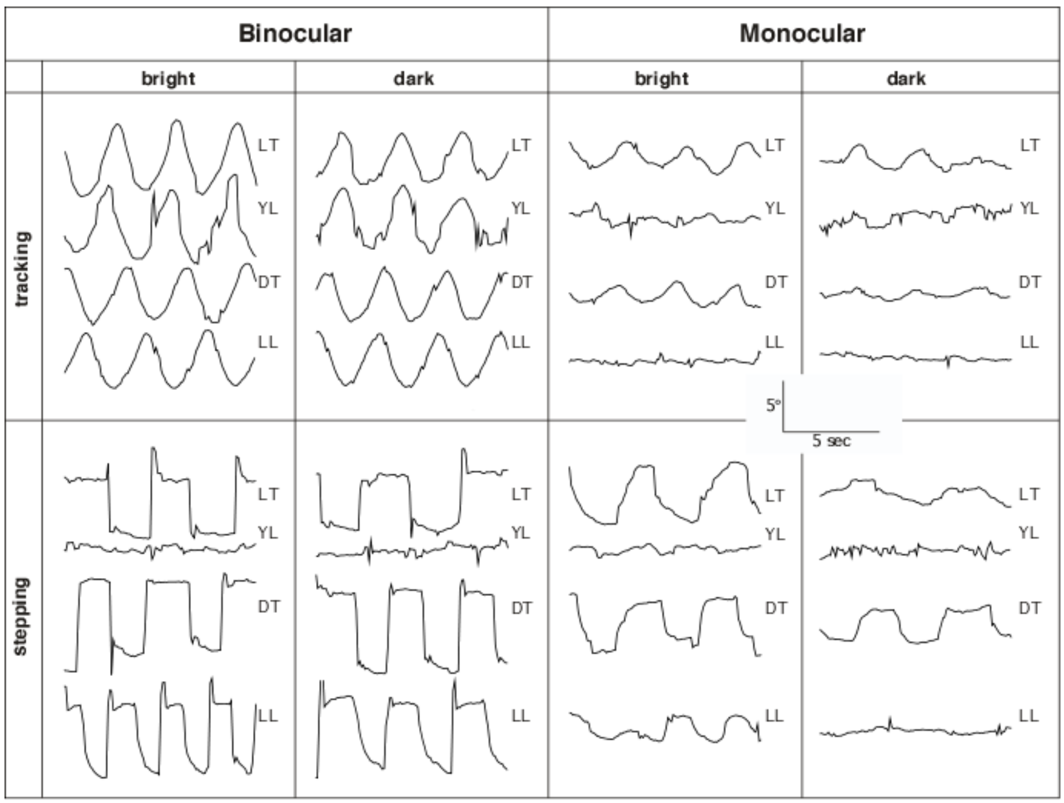

Figure 3.8. Sample version traces from each condition for the four observers who participated in the eye movement monitoring session in Experiment 2. The version component was computed by averaging the horizontal positions of the left and right eyes ((left + right)/2).

Table 3.3. Mean magnitudes (standard deviations) of the version component of each observer's eye-movements in the binocular and monocular conditions (in degrees). The version component was computed by averaging the horizontal positions of the left and right eyes ((left + right)/2).

	Binocular		Monocular	
Observers	Bright	Dark	Bright	Dark
Tracking Magnitude				
LT	4.95 (0.44)	4.85 (0.37)	2.46 (0.55)	1.20 (0.52)
YL	5.25 (1.83)	3.59 (2.00)	1.19 (0.49)	1.18 (0.46)
DT	5.14 (0.31)	4.69 (0.34)	2.17 (0.56)	1.18 (0.44)
LL	5.67 (0.42)	5.03 (0.23)	0.76 (0.39)	0.00** (0.00)**
Stepping Magnitude				
LT	6.89 (1.29)	6.82 (1.17)	4.93 (0.63)	2.14 (0.85)
YL				
DT	7.81 (1.47)	7.45 (0.97)	4.40 (1.12)	3.34 (0.52)
LL	7.11 (1.47)	6.70 (1.17)	1.70 (0.91)	0.60 (0.30)

Observers LT's, YL's and DT's eye movements

Although two of these observers LT and YL experienced the cyclopean illusion, they did not have the largest eye movements in the dark conditions. (Observer DT, who did not experience the illusion, had the largest eye movement in the dark/stepping condition.) This lack of a perfect association suggests that the magnitude of the version eye movement is not the sole determinant for experiencing the illusion in the dark condition.

Observer YL did not move her eyes as requested in the stepping condition (see sample data). In the tracking condition, however, she was able to track the moving stimulus, albeit not as well as did Observer LT. Her ability to track and inability to step is consistent with her experiencing the cyclopean illusion in the tracking condition, but not in the stepping condition.

Observer LL's and Erkelens's eye movements

In the dark/monocular condition, Observer LL's eyes did not move in the tracking condition, which is consistent with her not experiencing the cyclopean illusion, as well as her large exophoria for the stimulus at 15cm. She was the oldest observer (age 43) comparable in age with Erkelens (age 48), and her reduced accommodative range was expected. In the bright/monocular condition, the movement of Erkelens's eyes (reported in Erkelens, 2000) and the movement of Observer LL's eyes (reported here) were likely due to their ability to use the isotropic rate of change in retinal image size of the stimulus holder. It is likely that Erkelens's eye movements (or lack thereof) in the dark/monocular condition would be similar to those of Observer LL, because the accommodative stimuli in his experiment were closer than his reported accommodative near point of 30 cm.

Chapter Four: The Cyclopean Illusion Unleashed*

* Ono, H., Mapp, A. P., & Mizushina, H. (2007) The cyclopean illusion unleashed. *Vision Research, 47,* 2067-2075. doi:10.1016/j.visres.2007.03.001

Abstract

The cyclopean illusion is the apparent lateral shift of stationary stimuli on a visual axis that occurs when vergence changes. This illusion is predictable from the rules of visual direction. There are three stimulus situations reported in the literature, however, in which the illusion does not occur. In the three experiments reported here we examine those stimulus situations. Experiment 1 showed that an afterimage seen on a stimulus moving on the visual axis does not produce the illusion as reported in the literature but an afterimage seen on a screen does. Experiment 2 showed that the illusion occurs for an intermittently presented stimulus in contrast to what has been reported previously. Experiment 3 showed that a monocular stimulus presented against a random-dot background produced the illusion, also in contrast to what has been reported. The results were consistent with the rules of visual direction.

Introduction

The traditional view on how we judge the directions of visual objects has its roots in the writings of Ptolemy (ca. 100–175), Alhazen (965–1040), William Charles Wells (1757–1817), Joseph Towne (1806–1879), Joseph LeConte (1823–1901), Ewald Hering (1834–1918), and Hermann Helmholtz (1821–1894).[9] This view can be summarized as follows: (a) we judge the directions of objects as though we were viewing them from a point midway between our eyes (historically, this point has been referred to by terms such as the binoculus, the central eye, the egocentre, the double eye, the projection centre, the centre of visual direction, and the cyclopean eye; in this paper we use the term cyclopean eye) and (b) any stimulus on either visual axis is seen on the line passing through the intersection of the visual axes and the cyclopean eye. This view was derived, at least in part, from several illusions of direction (Mapp, Ono, & Howard, 2002).

One such illusion, which formed the basis of what may be referred to as the rules of visual direction, is the cyclopean illusion, so named by Enright (1988). This illusion refers to the apparent lateral shift of visual stimuli that occurs when one changes fixation or accommodation between two stimuli positioned along the visual axis of one eye. Historically, the cyclopean illusion has been reported by researchers of note, namely,

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[9] For discussions of Ptolemy see Howard and Wade (1996), Lejeune (1956), and Smith (1996). For Alhazen see his (1083/1989), and for a discussion of Alhazen, see Howard (1996). For Wells see his (1792), and for discussions of Wells see Wade (2003) and Ono (1981). For Hering, see his (1868/1977, 1879/1942), and for a discussion of Hering see Ono (1979). For Helmholtz, see his (1910/1962). For Towne, see his (1865, 1866, 1869, 1870), and for LeConte see his (1881, 1897). For a discussion of the work of Wells, Towne, LeConte, Hering, and Helmholtz together, see Wade et al. (2006).

Wells (1792), Helmholtz (1910/1962), and Hering (1868/1977, 1879/1942) when accommodation vergence was changed between the two stimuli, as illustrated in Figure 4.1.

Recently, however, the robustness of the illusion and thus the validity of the rules of visual direction have been questioned. Specifically, Enright (1988) reported that the illusion does not occur if the stimulus is an afterimage or if the stimuli are illuminated stroboscopically at a temporal frequency of 5 Hz. This result is interesting, because the rules of visual direction make no distinctions between the processing of (a) afterimages versus “real” images or (b) continuously versus stroboscopically illuminated targets. Erkelens (2000) reported that, under monocular conditions in a dark room, the illusion occurs for some observers, but if the stimuli are presented against a large random-dot background, it never occurs. These results are interesting, because they challenge the traditional view of how the visual system processes visual direction, and they offer an exciting possibility for advancements in visual science. Experiments 1, 2, and 3 were designed to re-examine the cyclopean illusion under Enright’s afterimage condition, and his intermittent illumination condition, and Erkelens’s monocular random-dot background condition, respectively.

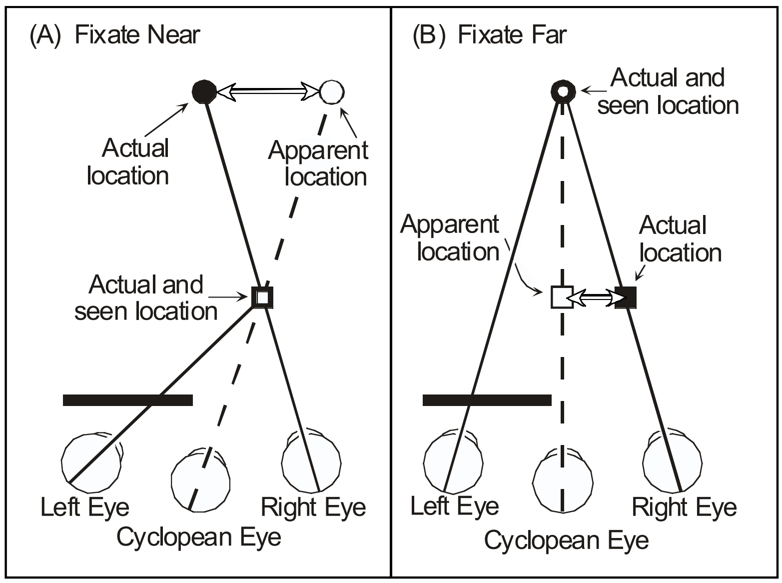

Figure 4.1. Illustration of two pairs of apparent locations of two stimuli as a function of a change in accommodative vergence: (A) Fixation on the near stimulus and (B) fixation on the far stimulus. The double lines with the arrows indicate the predicted apparent movement. The illustration is drawn as though the convergence were completely coupled with accommodation, but when the two stimuli are very close to the observer the occluded eye deviates from the indicated positions in the figure and the predicted extent of the apparent movement would be smaller.

There are four ways in which eye position can be changed in the stimulus situation used to create the cyclopean illusion (Erkelens, 2000): binocularly or monocularly tracking a moving stimulus in depth and binocularly or monocularly changing fixation or accommodation between two stimuli positioned along the visual axis of one eye. If the eye to which the stimuli are not aligned is covered, the eye movement eliciting the illusion is an accommodative vergence movement. If it is not covered, the eye movement eliciting the illusion is a disparity vergence movement. In Experiments 1 and 2 of this study, we examined the extent of the illusion produced by binocularly tracking the stimulus as Enright (1988) did and in Experiment 3 we examined the illusion using the four different kinds of eye movements used by Erkelens.

The theoretical interest of this stimulus situation is that it requires a distinction between headcentric and relative direction. See e.g., Khokhotva et al. (2005); Mapp et al. (2007); Ono, Lillakas, and Mapp (2003). The cyclopean illusion is one of headcentric direction, not relative direction. For the stimulus situation depicted in Figure 4.1, the apparent lateral shifts of the two stimuli occur with respect to the head. For the same stimulus situation, however, if the question were asked about whether the near and far stimuli are seen as collinear or in the same relative direction, the answer would correctly be “yes.” The nature of these two judgments is distinctly different, but the two aspects of the stimulus may not be completely independent for the visual system. If the stimuli were presented in front of a large background, which the visual system tends to keep perceptually stationary and if they were collinear with respect to a point on the background (i.e., they were is the same relative direction as the point), they might also appear to be stationary. In Experiment 3, backgrounds, which the visual system tends to interpret as being stationary, were placed right behind the far stimulus. Two of the backgrounds had markers that indicated the horizontal relative direction with respect to the two stimuli, while two other backgrounds did not. The expectation was that the backgrounds with the marker would tend to keep stationary (or to anchor) the stimuli collinear with respect to the marker.

Experiment 1

Enright (1988) created an afterimage on the fovea of one eye and then binocularly tracked a stimulus that moved back and forth along the visual axis of the stimulated eye. See Figure 4.2. He found that the afterimage appeared to move towards and away from him as though it was "attached" to the moving stimulus and that the apparent size of the afterimage followed Emmert's law (i.e., the afterimage appeared larger when it appeared farther away). He did not, however, experience any apparent leftward or rightward movement of the afterimage (i.e., he did not experience the cyclopean illusion). We hypothesized that the cyclopean illusion was not produced because the afterimage was seen on the tracking stimulus and appeared to move in depth with it. In other words, the afterimage was always seen at the intersection of the visual axes; Figure 4.1 shows that a requirement for the illusion to occur is that the target stimulus not be seen at the intersection of the visual axes continuously. We further hypothesized that if the afterimage were seen at a fixed distance other than the distance at which the visual axes intersected, the illusion would occur as shown in Figure 4.1 and 4.2. (Note in Figure 4.2 that changes in the predicted direction with respect to the cyclopean eye are the same for the moving stimulus and for the apparent shift of the far stimulus or the afterimage seen at the same distance as the far stimulus. This is so, because any stimuli on either visual axis are seen on the line passing through the intersection of the visual axes and the cyclopean eye.) We tested these hypotheses with the following two conditions: (a) a central afterimage seen on a tracking stimulus (replicating what Enright did) and (b) a peripheral afterimage seen on a screen located behind and slightly above a tracking stimulus. The expectations were that the first condition would replicate Enright's result and that the second condition would produce the cyclopean illusion without a change in the apparent size of the afterimage.

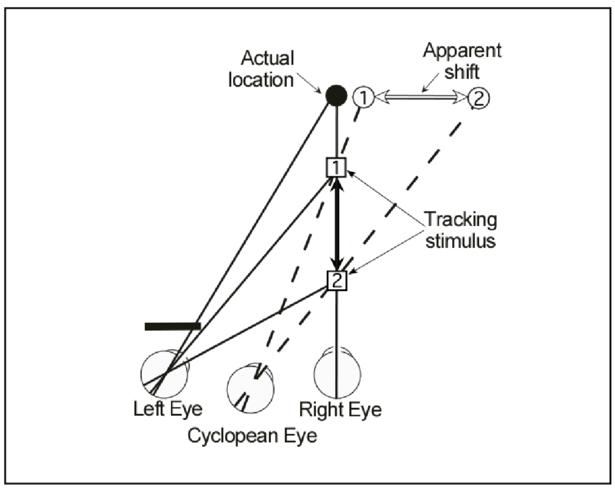

Figure 4.2. Illustration of the stimulus condition used by Enright (1988) and the predicted extent of the cyclopean illusion for a far stimulus for a given binocular eye movement. The double lines with the arrows indicate the predicted apparent movement when the intersection of the visual axes moves as indicated by the thick line with the arrows. (The figure is not scaled to the dimension of the stimulus locations in Experiment 1.)

Methods

Stimuli and Apparatus

A screen (84 cm high and 89 cm wide) subtending 42 deg by 44 deg and positioned 112 cm from the observer was used for the peripheral afterimage condition. A flashgun (Berkey Canadian "200" Model 83440) was placed on the left side of the screen to create an afterimage, and it was covered by a black cardboard with a circular aperture of 2 cm in diameter (1 deg. of visual angle). A personal computer (Apple iBook G3) generated the background stimulus and a projector (Electrohome EDP 58XL) back projected the background onto the screen. The background stimulus consisted of horizontal lines (0.2 cycles per degree sine waves) with vertically modulated luminance. The vertical edges were visible (22 degree away from the median plane), but did not seem to play a role in decreasing the extent of the apparent movement.

The far stimulus was a seven-segment LED (1 cm by 0.7 cm) displaying a '0' and remained at a distance of 110 cm (just in front of the screen). The tracking stimulus was a single, dim LED mounted on a rod that moved along a rail between 20 and 65 cm from the observer. The far LEDs and the near LED were positioned such that their horizontal positions were along the line of sight of the observer's right eye perpendicular to the face (Figure 4.2). They were offset vertically so that the far stimulus appeared higher than the tracking stimulus. A black cardboard occluder blocked the far stimulus from the observer's left eye. The tracking stimulus was visible to both eyes, but the far LEDs were only visible to the right eye. A bite-board stabilized the observer's head.

Procedure

A pre-experimental session, with two conditions, familiarized the observer with an afterimage and with reporting its perceived distance and perceived size. In the first condition, a central afterimage was created, and a sheet of cardboard was placed at 20, 40, 60, 80 cm from the observer or directly in front of the screen. The observer reported the perceived size and perceived distance of the afterimage, which appeared to be on the cardboard, while fixating on the sheet of cardboard positioned at the five different distances. In the second condition a peripheral afterimage was created. In this case, the observer reported the perceived size and perceived distance of the afterimage, which appeared to be on the cardboard, as the sheet of cardboard was placed at 40, 60, 80 cm or in front of the screen, while fixating a small LED, placed at a distance of 20 cm. No feedback as to the "correct" distance or size was given.

In the experimental session, the observer sat in a room in which the only visible light came from the LEDs and the screen. The right eye received the stimulation for the afterimage while the left eye was covered with an eye patch. In the central afterimage condition, the centre of the aperture on the flashgun was fixated when the flash was presented; in the peripheral afterimage condition, a point placed 5 deg below the aperture was fixated. The eye patch was removed after the afterimage was created. The observer was instructed to blink whenever the afterimage faded, because blinking helped to keep the afterimage visible. If the afterimage did not re-emerge, the procedure, described above, was repeated. The experimenter moved the tracking LED back and forth from 20 to 65 cm with a cycle of 6 s.

Each trial was comprised of two parts. In both parts, observers tracked the tracking stimulus as it moved back and forth along the visual axis of their right eye five times. During the first set of tracking movements, observers were instructed to report the perceived distance of the afterimage, and that of the LEDs, and the perceived size of the afterimage. They reported perceived distance by specifying, in centimetres, how far away the afterimage and the LED appeared, when they were at their closest point and their most distant point. They reported the apparent size of the afterimage, in centimetres, when it appeared at its closest point and at its most distant point. During the second set of tracking movements, observers were instructed to report the apparent lateral movement of the LEDs and the afterimage. They reported this apparent movement using the method developed by Khokhotva et al. (2005). Specifically, they were asked to imagine a line perpendicular to their face, passing through the LED or the afterimage and to report the magnitude of the apparent movement by stating where the imaginary line moved with respect to their face (e.g., “in front of my nose to 3 cm to the right of my right eye”).

Each observer performed one trial per condition. The central afterimage condition preceded the peripheral afterimage condition for three out of the five observers, and for the other two observers the conditions were reversed. The second condition was not started until the afterimage from the first condition had completely disappeared.

Observers

Five observers, two females and three males, from the York University community participated. One was the third author of this paper. All had normal or corrected to normal vision; four observers were naïve as to the purpose of the experiment.

All observers in this experiment as well as in the other two experiments provided their written consent.

Results and Discussion

The results from our central afterimage condition were consistent with those reported by Enright (1988). All observers reported that the imaginary line perpendicular to the face and passing through the afterimage always pointed to the same part of their face ("in front of the right eye" or "between the nose and the right eye") and did not move laterally; but the far stimulus appeared to move laterally (M = 11.50 cm, SD = 5.29). The predicted magnitude of apparent lateral movement of the far stimulus was 12.00 cm, which is close to the obtained mean magnitude. All observers reported that the afterimage appeared on the tracking stimulus and that it appeared to move towards and away from them with it. The perceived size of the afterimage increased gradually while the tracking stimulus was moving away, and vice versa. The perceived distances and sizes of the afterimage are presented in the Appendix at the end of this chapter.

In the peripheral afterimage condition, all observers reported that the imaginary perpendicular line passing through the afterimage moved laterally when the tracking stimulus moved back and forth. The imaginary line typically pointed to the right eye or between the nose and the right eye, when the tracking stimulus was at its farthest distance; it moved toward the right side of the face as the tracking stimulus approached them. The direction of the movement was consistent with our prediction (i.e., when the tracking stimulus moved toward the observer, the afterimage appeared to move rightward or outward). The mean magnitude of the apparent lateral movement of the imaginary line passing through the afterimage was 11.30 cm (SD = 5.14); the obtained mean was close to the prediction of 12.00 cm. The obtained mean of 11.30 cm was statistically different from the value of zero (i.e., no lateral movement), $t(4) = 4.91$, $p < .01$. The far stimulus appeared to move in the same way as the afterimage whereas the tracking stimulus did not appear to move laterally, as in the central afterimage condition. All observers reported that the afterimage always appeared at the screen (i.e., fixed distance), and it remained the same size. The perceived distance and size data are presented in the Appendix at the end of this chapter.

The conclusion to be made from the results of Experiment 1 is that the afterimage *per se* is not responsible for the lack of the cyclopean illusion in Enright's (1988) experiment. According to the rules of headcentric visual direction the illusion of an apparent lateral shift is predicted for stimuli that appear behind the binocularly fixated point (or in front of it), or for stimuli that remain at a fixed distance as in Figure 4.1 and 4.2. Our peripheral afterimage condition confirmed this prediction; all observers reported the predicted illusion. The afterimage appeared to move in the same way as the far stimulus depicted in Figure 4.2. According to the rules, a binocularly fixated stimulus is predicted to appear where it is, and if the afterimage moves with the fixated stimulus, the afterimage would not move laterally. Our central afterimage condition confirmed this prediction.

Experiment 2

Mackay (1958) reported that motion perception is suppressed when one views a stroboscopically illuminated object while gently tapping on the viewing eye, whereas it is not suppressed if the object is continuously visible. Based on this report and on a personal communication with Mackay, Enright (1988) examined the cyclopean illusion under stroboscopic illumination conditions. Specifically, he reported that a monocular target that is stroboscopically illuminated does not undergo any apparent lateral shifts (i.e., the cyclopean illusion does not occur), when one tracks a binocular stimulus that moves back and forth along the visual axis of the eye that sees the background target. We conducted several informal experiments, using the apparatus from Experiment 1, in an attempt to replicate Enright's observation. We first presented a 2 cm square stimulus on the screen with a temporal frequency of 5 Hz and with one of four different duty cycles [8.35% (one video frame), 16.7%, 25.0%, and 50.0%]. All observers reported the cyclopean illusion, when they tracked the tracking stimulus as in Experiment 1. We then tried flickering the target stimulus alone or together with the background on the screen, but in either case the illusion did not disappear. Instead of formalizing these experiments, we formalized an experiment that matches as closely as possible Enright's stimulus condition (i.e., viewing distance and the extent of the movement of the tracking stimulus). Because we had no basis on which to guess the stimulus size or the location of the stroboscope in his study, we varied the size of the stimulus and the position of the stroboscope (i.e., "behind" or "in front of" the observer). The light source illuminated the tracking stimulus and the target together, when it was behind the observer; it illuminated the target directly but the tracking stimulus indirectly, when it was in front of the observer. These two conditions were designed to determine whether the intermittent illumination of the tracking stimulus would interfere with the tracking eye movements and inhibit the cyclopean illusion.

Methods

Stimuli and Apparatus

A white sheet of cardboard (5, 10, 20, 40 or 80 cm square) served as the target stimulus and was placed on a black wall at a distance of 5 m. The horizontal centre of the target was positioned on the visual axis of the right eye, and the bottom edge was always positioned at the same level. The tracking stimulus was a small, dim LED mounted on a rod; it moved back and forth along the visual axis of the right eye between 20 and 65 cm from the observer. The LED, viewed binocularly, moved along an optic bench perpendicular to the face and moved toward and away from the right eye as shown in Figure 4.2. The target stimulus appeared slightly above the LED and was visible monocularly. A black cardboard in front of the left eye occluded the target stimulus from that eye, and a bite board stabilized the head.

A stroboscope (General Radio Company, Strobotac Type 1531-AB) illuminated the target stimulus and the wall with a temporal frequency of 5 Hz (strobe condition) or 400 Hz (no strobe condition) that was well above the critical flicker frequency. The stroboscope was placed 1.2 m in front of the observer, or 2.5 m behind and above the observer. It directly illuminated the tracking stimulus as well as the target stimulus on the wall, when it was behind the observer. The intermittent illumination of the rod upon which the small LED was mounted was noticeable, when the stroboscope was behind the observer, but not when the stroboscope was in front of the observer. The small LED itself was continuously on and visible regardless of where the stroboscope was located.

Procedure

The experimenter moved the tracking stimulus back and forth five times with a cycle of 6 s. The observer tracked the tracking stimulus binocularly. After each stimulus presentation, observers reported whether the target stimulus on the wall appeared to move laterally; they reported the direction (leftward or rightward) and the magnitude of the apparent movement in centimetres. After reporting the percept, they closed their eyes until the experimenter positioned the target stimulus for the next trial. Each observer performed one trial for each of the 20 conditions: 2 illumination conditions (strobe and no strobe) x 2 stroboscope positions (in front of and behind the observer) x 5 target stimulus sizes (5, 10, 20, 40, 80 cm). The conditions were presented in random order in a single session.

Observers

Six observers, two females and four males, from the York University community participated. One was the third author of this paper. All had normal or corrected to normal vision. Five observers were naïve as to the purpose of the experiment.

Results and Discussion

All observers experienced the cyclopean illusion in all of the conditions. The perceived direction of the illusion was always consistent with our prediction (i.e., when the tracking stimulus moved towards the observer, the target appeared to move rightward.) The reason Enright (1988) did not find the illusion with a strobed stimulus remains a mystery. Perhaps, Enright's reports were that a smooth apparent motion is not seen. If that is the case, we concur. What we report as an apparent movement in the strobe condition is better described as a series of apparent displacements. In any event, the mean magnitudes of the illusion are shown in Figure 4.3.

We performed a three-way repeated-measures ANOVA on the perceived magnitudes of the illusion with the factors: illumination type (strobe, no-strobe), position of illumination (in front of or behind), and target size (5, 10, 20, 40 and 80 cm). The analysis revealed a significant main effect for the target size, $F(4, 20) = 5.77$, $p < .05$. All other main effects and interactions were not significant. These results show that stroboscopically illuminating the target stimulus alone or together with the tracking stimulus does not suppress the occurrence of the cyclopean illusion.

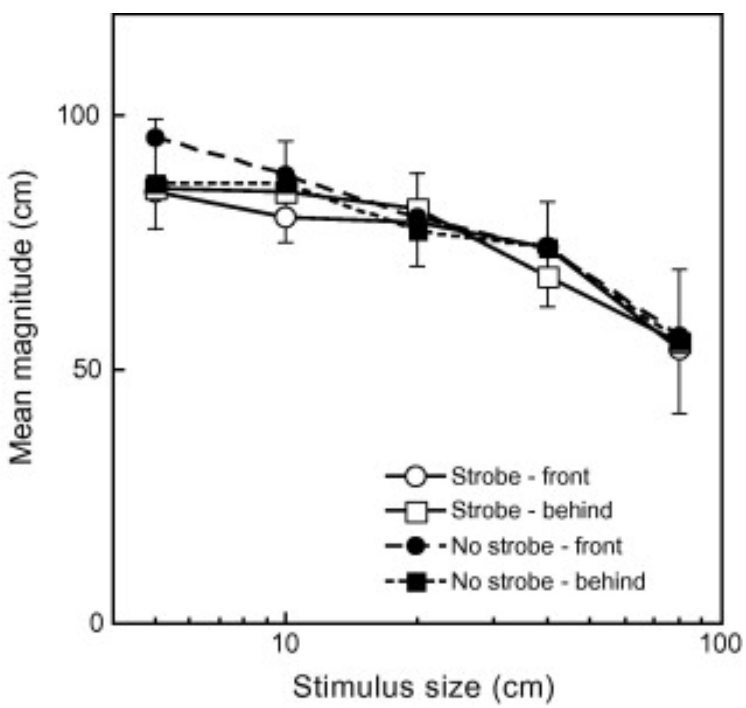

Figure 4.3. Mean magnitudes of the cyclopean illusion as a function of stimulus size on the background for four different conditions. (Error bars represent ±1 standard error of the mean.)

Our significant target size effect extends Erkelens's (2000) finding that the cyclopean illusion diminishes, when the stimuli are presented in front of a large random-dot background. His finding was obtained in a condition in which both the tracking stimulus and the background were seen monocularly. In our condition the tracking stimulus was seen binocularly and the background was seen monocularly. Therefore, our results indicate that the effect of background size generalizes to the results obtained while tracking a binocular stimulus. Our interpretation of these results (Erkelens's and ours) is that the large backgrounds are interpreted by the visual systems as stationary. We explore this interpretation in Experiment 3.

Experiment 3

Erkelens (2000) reported that the cyclopean illusion (a) does not occur, for most observers, if the stimuli are viewed monocularly, and (b) never occurs, for any observers, if the monocularly viewed stimuli are presented in front of a large random-dot background. We (Ono, Mapp, & Howard, 2002) have shown previously that part of the reason for the absence of a monocular cyclopean illusion in Erkelens's (2000) study was that his stimuli did not produce a large enough eye movement. In Experiment 3, the required extent of the eye movement was larger than that used by Erkelens's. Additionally, we hypothesized that the random-dot background against which his stimuli were presented inhibited the illusion. Our hypothesis was that a dot(s) on the background pattern provided a salient reference point (i.e., a horizontal landmark) that "anchored" the relative directions of the stimuli (the near and far LEDS) with respect to the background. The bases for this hypothesis were: (a) a large background is likely to be interpreted by the visual system as stationary, and (b) the relative direction of the dot on the random-dot background and the two aligned stimuli remains the same before and after the vergence eye movement. In this experiment we tested this hypothesis by measuring the extent of the cyclopean illusion in the presence of two anchoring and two non-anchoring backgrounds. The two anchoring backgrounds consisted of a random-dot pattern and a series of vertical lines. The non-anchoring backgrounds consisted of a series of horizontal lines and a black screen. We measured the extent of the cyclopean illusion, in the presence of these four backgrounds, under two viewing conditions (binocular and monocular) and with two types of eye movement (tracking and stepping).

Methods

Stimuli and Apparatus

The screen and the projector used to present the background patterns were the same as in Experiment 1. Also, as in Experiment 1, the far stimulus was a seven-segment LED (1 cm by 0.7 cm) that displayed the digit ‘0’ at a distance of 110 cm (just in front of the screen). Unlike Experiment 1, the tracking stimulus was identical to the far LED, instead of a single, dim LED. The tracking LED was changed because a small LED is known to be an inadequate stimulus for monocular accommodation (Aggarwala et al., 1995; Owens & Leibowitz, 1975). The tracking LED served as a fixed near stimulus in the stepping conditions and for those conditions it was positioned at a distance of 25 cm.

Unlike Experiments 1 and 2, the LEDs (and the rail of the optic bench) were aligned to one eye, and the far LED was in the median plane. This made the stimulus condition similar to that of Ono, Mapp, and Howard (2002) and to that illustrated in Erkelens’s (2000) Figure 2. The details of the four background patterns were as follows. The random-dot pattern consisted of small black dots (0.5 deg diameter) with a density of approximately 1100 dots/m^2 on a white screen. The luminance of the vertical and horizontal patterns was sine modulated (0.2 cycles per degree) horizontally and vertically, respectively. The horizontal lines were the same as in Experiment 1; the vertical edges were visible but the results of Experiment 1 showed that they did not appreciably decrease the extent of the illusion. For the dark background the projector was turned off, and the only visible light was that from the two LEDs. The random-dot and the vertical-lines background served as anchoring stimuli, and the horizontal-lines and the dark backgrounds served as non-anchoring stimuli.

Procedure

In all conditions, the background stimulus and the far LED were seen monocularly and only by the eye with which the near and the far LEDs were aligned. Thus, the monocular and binocular viewing conditions refer only to how the tracking or the near LED was viewed. This is consistent with Erkelens's (2000) definition of his monocular and binocular conditions. The binocular tracking condition was like that of Enright's (1988) and our Experiments 1 and 2: the near LED moved back and forth along the optic bench from a distance of 25 cm to 65 cm and was viewed binocularly. In the monocular tracking condition, the same stimulus was viewed monocularly (an eye patch covered the eye to which the stimuli were not aligned). In both conditions, the experimenter moved the closer LED along the rail of the optic bench, back and forth twenty times, with a cycle of 3 s.[10] The observer's task was to track the moving LED.

In the binocular stepping condition, the observers viewed the stationary near LED, from a distance of 25 cm, with both eyes, and the stationary far LED from a distance of 110 cm, monocularly. In the monocular stepping condition, the same stimuli were presented but the eye to which the LEDs were not aligned was covered with an eye patch. Figure 4.1 illustrates this condition. In both conditions, the observer's task was to fixate the two LEDs alternately, twenty times at a "comfortable" pace. Additionally, the observers were instructed to focus on the fixated stimulus carefully throughout the experiment. The extent of the eye movements in the stepping condition was greater than that in the tracking condition as in Erkelens's (2000) Experiment 3.

There were 32 conditions (stimuli aligned to the right or to the left eye x binocular or monocular x stepping or tracking x four different backgrounds). The conditions for which the stimuli were aligned to the right or left eye were presented in different sessions. Within those sessions, 16 conditions were presented in random order.

After each stimulus presentation, the observers answered the following four questions: (a) Did you see any movement of an imaginary line that would pass through the two LEDs?; (b) In which direction (leftward or rightward) did the far end of the imaginary line move?; (c) Where was the apparent pivot point of the imaginary line

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[10] We doubled the average speed of the tracking stimulus relative to that of Experiments 1 and 2, because observers reported in a preliminary experiment that it was easier to judge the extent of apparent movement with a cycle of 3 s than with a cycle of 6 s.

(when movement was seen) or where did the line appear to point to your face (when no movement was seen)? (i.e., in front of your nose, in front of your eye, close to your nose, close to your eye, or between your nose and eye); (d) How much did the far LED move laterally in centimetres or millimetres?

Observers

Sixteen observers participated in Experiment 3. All had normal or corrected-to-normal vision. All were naive as to the purpose of the experiment except for the third author of this paper.

Results and Discussion

All observers experienced the cyclopean illusion in all the binocular conditions. Also, all observers experienced the illusion in at least one of the monocular non-anchoring conditions and all but two of the observers experienced the illusion in the monocular anchoring conditions. (These findings from our monocular conditions contrast with Erkelens's (2000) study in which only four out of 12 observers experienced the illusion.) All observers reported in at least eight trials that the imaginary line passing through the two LEDs pivoted in front of the nose or close to the nose (when they experienced the illusion) or pointed to near the front of the nose or close to the nose (when they did not experience the illusion). In at least one trial, 37.5 % of observers responded, "in front of the eye" or "close to the eye." The reference point for visual direction or the cyclopean eye not being reported at the bridge of the nose in all trials is likely due to the observers knowing the actual locations of the stimuli; we made no attempt to hide the actual locations as in Khokhotva et al. (2005). To examine the apparent pivot location quantitatively, we assigned the values 0, 1, 2, 3 and 4 to "in front of the nose," "close to the nose," "between the nose and the eye," "close to the eye," and "in front of the eye," respectively. The means were 0.73 (SD = 0.80) and 0.78 (SD = 0.87) in the binocular and monocular conditions, respectively. It is noteworthy that the value 0.78 in the monocular condition is closer to '0' (i.e., "in front of the nose"), which is predicted by the rules of headcentric direction, than to '4' (i.e., "in front of the eye"), predicted by Erkelens (2000).

Because the variances in the binocular conditions were noticeably larger than in the corresponding monocular conditions, the mean extent of the illusion in each condition for each observer was transformed logarithmically for the analyses. The geometric mean extents of the cyclopean illusion as a function of the different backgrounds are shown in Figure 4.4. These means were analysed with a 2 x 2 x 4 repeated-measures ANOVA (binocular vs. monocular, stepping vs. tracking, and four different backgrounds). The analysis yielded no significant interactions but all three main effects were significant: viewing conditions, $F(1,15) = 75.28$, $p < .001$; eye movement conditions, $F(1,15) = 4.72$, $p < .05$; and background conditions, $F(3,45) = 26.29$, $p < .001$.

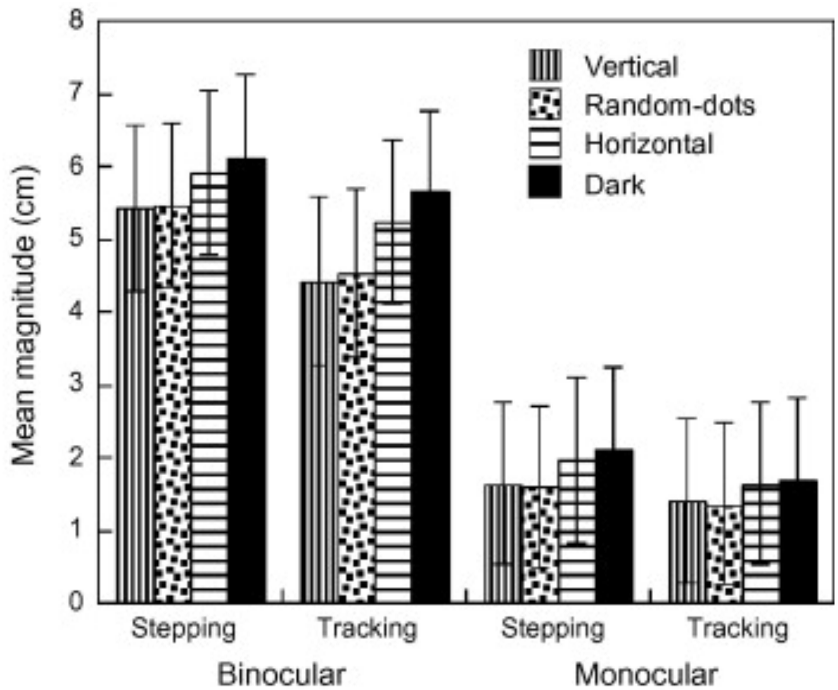

Figure 4.4. Geometric mean magnitudes of the cyclopean illusion as a function of different backgrounds. (Error bars represent ±1 standard error of the mean.)

To understand the source of the significant differences among the four backgrounds, we performed all possible pair-wise comparisons with a Bonferroni correction. Table 4.1 shows the pair-wise comparisons for the binocular and monocular conditions together and separately. Table 4.1 and Figure 4.4 together show that in all but one instance the illusion was significantly smaller in the anchoring conditions than in the non-anchoring conditions (see inside the framed rectangle area in Table 4.1). The non-significant difference was between the random-dot and the horizontal line backgrounds in the binocular condition, $p = .057$. None of the comparisons between any two of the anchoring conditions or between any two of the non-anchoring conditions were statistically significant. These comparisons show that the anchoring backgrounds diminished the cyclopean illusion.

No theoretical significance should be attached to the statistical difference between the two types of eye movement (stepping vs. tracking) conditions, because the required eye movements were different as in Erkelens's (2000) experiments. It is likely that the stepping conditions produced a larger cyclopean illusion than the tracking conditions because the extent of the vergence eye movement was larger in the stepping conditions.

What is of theoretical significance, however, is that the binocular conditions produced a larger illusion than the monocular conditions. This is likely the result of the disparity-driven vergence eye movements in the binocular conditions, being larger than the accommodation-driven vergence eye movements in the monocular conditions. For evidence supporting this claim, see Ono, Mapp, and Howard (2002).

Table 4.1. The statistical significance of the pair-wise comparisons with Bonferroni correction in Experiment 3. The pair-wise comparisons between the anchoring and the non-anchoring conditions are inside the framed rectangle.

			Anchoring		Non-anchoring	
			Vertical	Random-dots	Horizontal	Dark
Anchoring	Vertical	Overall		n.s.	$p < .01$	$p < .01$
		Binocular		n.s.	$p < .05$	$p < .05$
		Monocular		n.s.	$p < .01$	$p < .01$
	Random-dots	Overall			$p < .01$	$p < .01$
		Binocular			n.s.	$p < .01$
		Monocular			$p < .01$	$p < .01$
Non-anchoring	Horizontal	Overall				n.s.
		Binocular				n.s.
		Monocular				n.s.
	Dark	Overall				
		Binocular				
		Monocular				

Our findings cast doubt on Erkelens's (2000) claim that the visual directions of monocularly seen stimuli are specified from the viewing eye and that "perceived direction during monocular viewing is based on signals of the viewing eye only" (p. 2411). This is so, because Erkelens's claim is predicated on (a) the cyclopean illusion not occurring in monocular conditions, and (b) his monocular condition producing the same extent of vergence eye movement as in his binocular condition. Moreover, the findings of this study indicate that his use of a random-dot background may have contributed to the elimination of the illusion for those of his observers who did experienced the illusion without a background.

General Discussion

The results of the three experiments confirm the observations made by Wells (1792), Helmholtz (1910/1962), and Hering (1868/1977, 1879/1942). The cyclopean illusion seems relatively robust, despite doubts raised by Enright (1988) and Erkelens (2000), when certain requirements of the stimulus conditions are met. The results of Experiment 1 indicate that whether the monocular stimulus is an afterimage or a real stimulus, it must be seen at a fixed distance behind (or in front of) the intersection of the visual axes. The results of Experiment 2 indicate that the illusion does occur for an intermittently illuminated stimulus, but we were unable to uncover the reason why Enright did not obtain a similar result. The results of Experiment 3 together with those of Ono, Mapp, and Howard (2002) suggest that the vergence eye movements must be sufficiently larger than those of Erkelens's experimental setup for most observers to see the illusion in the monocular conditions. Moreover, the results of Experiment 3 indicate that having a large background with salient landmarks for horizontal position anchors the stimuli and reduces the magnitude of the illusion.

As we found in Experiments 2 and 3, there are several recent studies that show that a monocular stimulus does not always follow the predictions from the rules of visual direction (Erkelens & van Ee, 1997a, 1997b; Ono & Mapp, 1995; Shimono & Tam, 2002; Shimono et al., 1998; Shimono et al., 2005). The common denominator in all of those studies and in Experiments 2 and 3 of this study is that the monocular stimulus is embedded in a large visual field. To understand these findings, the results of this study suggest that the distinction between relative and headcentric visual direction is critical. See Khokhotva et al. (2005), Mapp et al. (2002, 2007), and Ono, Lillakas, and Mapp (2003) for a more detailed discussion.

Appendix

The mean perceived distances and sizes of the afterimage in the central and peripheral afterimage conditions of Experiment 1 are presented in Figure 4.5. The shaded and unshaded bars in the graph represent data from the central and peripheral afterimage conditions, respectively.

In the central afterimage condition, all observers reported that the afterimage appeared on the tracking stimulus and that it appeared to move towards and away from them with it. The mean perceived distance of the afterimage and that of the tracking stimulus were always the same: they were 13.00 cm (SD = 4.47) when they appeared closest, and 59.00 cm (SD = 12.45) when they appeared farthest. The perceived size of the afterimage increased gradually while the tracking stimulus was moving away, and vice versa. The mean perceived sizes of the afterimage for the nearest and the farthest distances were 0.38 cm (SD = 0.13) and 1.24 cm (SD = 0.34), respectively.

In the peripheral afterimage condition, all observers reported that the afterimage always appeared at the screen (i.e., fixed distance), and it remained the same size. The mean perceived distance and the mean perceived size of the afterimage were 114.00 cm (SD = 21.91) and 3.70 cm (SD = 2.77), respectively.

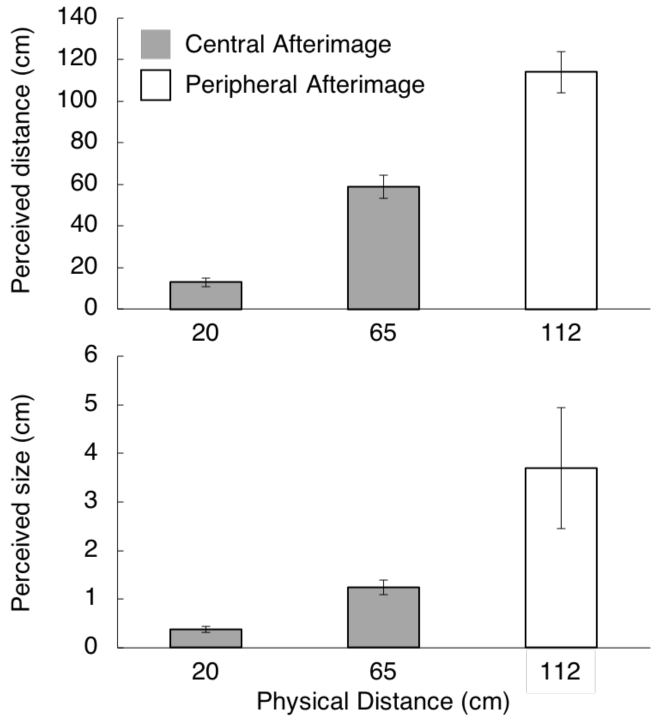

Figure 4.5. Mean perceived distance (upper panel) and perceived size (lower panel) of the afterimage in Experiment 1. Error bars represent ±1 standard error of the mean.

Chapter Five: Hitting the Target: Relatively Easy, Yet Absolutely Difficult*

* Mapp, A. P., Ono, H., & Khokhotva, M. (2007). Hitting the target: Relatively easy, yet absolutely difficult. *Perception, 36,* 1139–1151. doi:10.1068/p5677

Abstract

It is generally agreed upon that absolute direction judgments require information about eye position, whereas relative direction judgments do not. The source of this eye position information, particularly during monocular viewing, is a matter of debate. It may be either binocular eye position or the position of the viewing eye only that is crucial. Using more ecologically valid stimulus situations than the traditional LED in the dark type experiment, we performed two experiments. In experiment 1, observers threw darts at targets that were fixated either monocularly or binocularly. In experiment 2, observers aimed a laser gun at targets while fixating either the rear or the front gunsight monocularly or the target either monocularly or binocularly. We measured the accuracy and precision of the observers' absolute and relative direction judgments. We found that (a) relative direction judgments were precise and independent of phoria and (b) monocular absolute direction judgments were inaccurate, and the magnitude of the inaccuracy was predictable from the magnitude of phoria. These results confirm that relative direction judgments do not require information about eye position. Moreover, they show that binocular eye position information is crucial when judging the absolute direction of both monocular and binocular targets.

Introduction

We have argued elsewhere (Khokhotva et al., 2005; Mapp & Ono, 1999; Mapp et al., 2002, 2003; Ono, Mapp, & Howard, 2002) that there is ample evidence to show that we perceive the visual directions of objects as though from the midpoint between the two eyes, the cyclopean eye. Moreover, we have argued that this idea applies equally to both monocularly and binocularly seen stimuli. Erkelens (2000) and Erkelens and van Ee (2002), however, have challenged this idea. Specifically, they have argued that the visual directions of monocularly seen stimuli are specified from the viewing eye and that "perceived direction during monocular viewing is based on signals of the viewing eye only" (Erkelens, 2000, p. 2411). Moreover, they argued that the concept of a cyclopean eye is irrelevant for vision. Given the abundance of evidence confirming the relevance of the cyclopean eye, a question that arises is how can all of this evidence be ignored. According to Erkelens and van Ee, this body of evidence is not compelling because it is based on poorly conducted experiments. They state, "we are astounded that results of many poor experiments from the literature carry so much weight" (Erkelens & van Ee 2002, p. 1162).

Admittedly, much of the previous evidence, collectively questioned by Erkelens and van Ee (2002), comes from "artificial" or non-ecologically valid stimulus situations. The traditional experiments often required observers to fixate at one distance while judging the direction of an object – typically a small point source of light - located at a different distance. We seldom perform such a task in a "natural" setting; instead we are more accustomed to fixating the stimulus of interest. It is possible, then, that the well-established laboratory findings may be difficult to relate to daily perceptual experiences.

In this paper we reassess the relevance of the laws of visual direction and the concept of the cyclopean eye using stimulus situations and response characteristics that are more ecologically valid, realistic, and "natural" than those used previously.

The stimulus situations we examined involved throwing darts and aiming a rifle or a pistol at visual targets. These tasks allowed us to examine and quantify the distinction between relative and absolute directions. Relative direction judgments are made with respect to an external reference point, such as another object. Aiming a rifle involves relative direction when the sights of the rifle are made collinear with respect to the target. Retinal images, projected by an object of interest and the reference point, provide all the necessary information to make such judgments. Because only retinal information is required, relative direction judgments can be made with a high degree of precision (Ono, Lillakas, & Mapp, 2003). Absolute direction judgments can be made in several different frames of reference, that is, with respect to the median plane of the observer's body (such as head, torso, etc.).[11] Throwing a dart or aiming a pistol requires

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[11] Nicholas J Wade, the action editor for this paper, suggested that the term "egocentric direction" is better than the term "absolute direction", because what we termed absolute is relative to an observer. We agree, but we kept the term "absolute", because (a) The term "absolute" contrasts with the term "relative", (b) we have several recent publications using the term "absolute direction", and (c) the term "absolute direction" is analogous to the term "absolute distance" in that they are both specified with respect to the observer. (See Gogel and Tietz (1980) for a discussion of absolute distance.) For visual distance and visual direction, however, a different consideration is required. For visual distance, the part of the body from which the distance is specified does not appreciably alter the judgment. For visual direction, however, what is specified from the head and what is specified from the torso can be quite different depending on head

information about direction with respect to the torso. To make torso-centric judgments, three sources of information are required: position of the images on the retinas (retinal component), position of the eyes in the head (oculomotor component), and position of the head (head/body component) with respect to the torso (Mapp et al., 2002). Because more sources of information are required to make an absolute judgment than a relative judgment, the former tends to be less precise (Ono, Lillakas, & Mapp, 2003).

Khokhotva et al. (2005) argued that the distinction made above is critical for understanding the results of visual direction studies. Moreover, they speculated that the primary reason for the recent controversy is due to researchers neglecting to make this distinction. (Also see Ono, Mapp, & Howard, 2002; Mapp et al., 2002.) For example, Erkelens (2000) dealt with relative direction whereas the traditional treatment of visual direction deals with absolute direction. The distinction between relative and absolute direction is particularly important in understanding monocular visual direction. Judging only the relative visual direction in an experiment likely leads to the erroneous conclusion that (a) the cyclopean eye is located in one eye (e.g., Khan & Crawford, 2001) or (b) that the eye position of only the viewing eye is used (Erkelens, 2000). It is likely, because stimuli physically collinear with respect to an eye also appear as collinear. These two conclusions (a and b, above) are theoretically the same, because they place the origin of visual direction directly in one eye. That is, to state that the position of only one eye is used is equivalent to stating that the origin of visual direction is in that one eye. Without

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position. Throwing a dart or aiming a pistol requires torso-centric direction, and for the purpose of this paper, the term “absolute direction” can be interchanged with the term “torso-centric direction”.

knowing the absolute visual directions of the collinear stimuli (i.e., the point on the observer's body to which the stimuli appear collinear), no valid inferences about the location of the cyclopean eye can be made.

In experiment 1,we examined the accuracy and precision of throwing a dart when the target was viewed monocularly or binocularly. In experiment 2 we compared the accuracy and precision of aiming a rifle to that of aiming a pistol while accommodating either to the sights on the rifle or to the target. The hypothesis for both experiments was that binocular eye position information is used when judging monocular absolute direction.

Experiment 1

The preferred way of throwing a dart, amongst professional dart throwers, is to do so by performing an absolute direction task. That is, they estimate the torso-centric direction of the target and then using a well-practiced arm motion, throw the dart. (See Appendix.) It is conceivable that dart throwing can be performed as a relative direction task (although, as discussed in Appendix, this is not typical). For example, a dart thrower can "rehearse" an arm movement that would produce the correct trajectory for the dart to hit the target by making the arm movement and the target collinear with the viewing eye. This arm movement would launch the dart in the correct horizontal direction of the target; the correct vertical direction would depend on how hard the dart is thrown to counter the gravitational pull. In this experiment, however, we tried to stay true to the sport and required our observers to throw darts as an absolute direction task under both monocular and binocular viewing conditions. To prevent the "rehearsal" mentioned above, a blinder was placed on the side of the throwing arm so that the observers could not see the dart or their hand while aiming for their throw. Our prediction was that monocular viewing would produce a constant error but binocular viewing would not. Since the target was located at the regulation distance of 237 cm, most observers were expected to be esophoric; therefore, a constant error in the direction of the viewing eye was expected. [For a discussion of the relationship between phoria and viewing distance see Holland (1958), Ono and Weber (1981), and Owens and Tyrrell (1992).] That is, for most observers, the non-viewing eye would deviate inward, and the common axis (the line passing through the intersection of the two visual axes and the cyclopean eye) would shift toward the viewing eye pivoting at the cyclopean eye. This prediction is based on the law of visual direction that states that an object on a visual axis is seen on the common axis. See Figure 5.1. Moreover, it was also expected that observers with greater esophoria (i.e., greater shifts of the common axis) would produce greater constant errors.

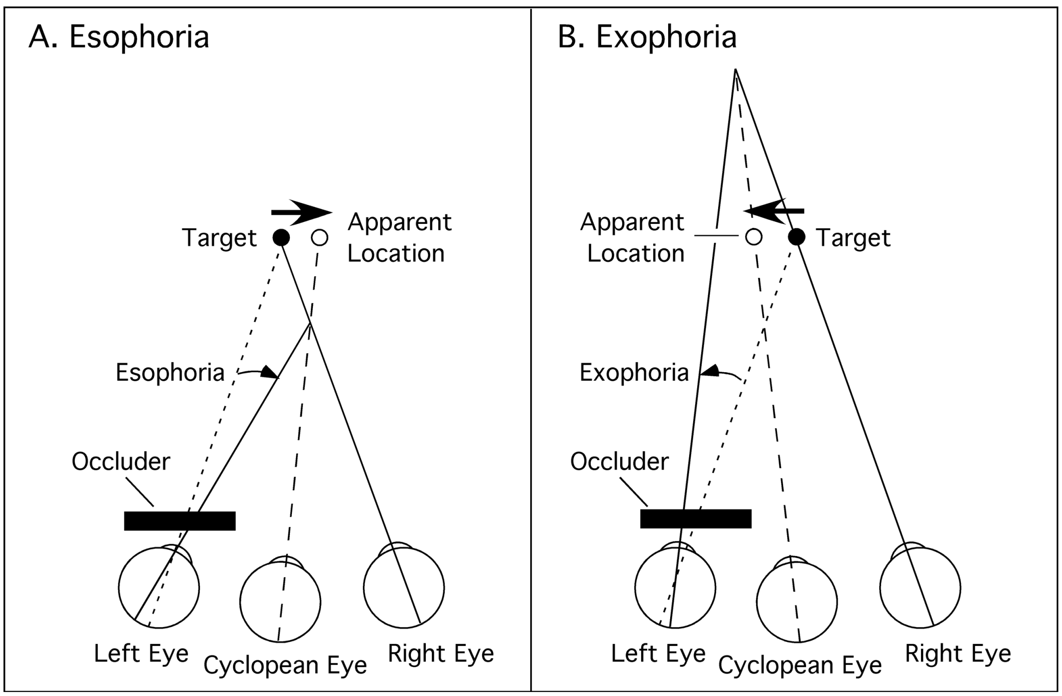

Figure 5.1. Illustration of the apparent location of a target as predicted by the laws of visual direction. In (A), an esophoric eye deviates inward, and the target appears shifted toward the seeing eye. In (B), an exophoric eye deviates outward, and the target appears shifted toward the non-seeing eye. Depicted are the predicted head-centric visual directions; for the predicted torso-centric directions the visual system needs to incorporate the orientation of the head with respect to the torso.

Methods

Apparatus

The apparatus consisted of a 100 cm wide by 70 cm high styrofoam board mounted on a wall 237 cm from the observer. The target was a red circle drawn on the centre of the board at a height of 173 cm from the floor. In addition, a vertical line, which divided the board into two equal halves, was drawn to assist the experimenter in measuring how many centimetres to the right or left of the target the dart landed. Errors to the right of the target were assigned positive values while those to the left were assigned negative values.

Additional equipment included 20-gram darts, an eye-patch for the monocular conditions, and a pair of liquid crystal goggles, which were designed to block the observer's view once s/he released the dart

Procedure

The experiment was conducted in a normally illuminated room and the observers threw the darts with their preferred hand. The observers wore a pair of liquid crystal goggles that allowed the experimenter to occlude their vision as soon as the dart was released. This ensured that the observers did not receive any feedback as to the accuracy of their throw. Additionally, a blinder was mounted on the throwing arm side of the goggles to ensure that the observers could not see either the dart or their hand.

The experiment was conducted in 10 blocks, each consisting of three practice trials, nine experimental trials, and six phoria measurements. During practice trials, observers threw the dart while fixating the target binocularly, and they were given feedback about the accuracy of their throws (i.e., the liquid crystal goggles were not activated). Practice trials were followed by experimental trials. No feedback was given to the observers during these trials.

For the experimental trials there were three fixation conditions (binocular, right eye only, and left eye only), and three standing positions (directly in front of the target, 50 cm to the left of the target, and 50 cm to the right of the target). Within each block, each observer performed each one of these nine possible throwing conditions once, and the order of the trials was randomized. The horizontal distance between the target and where the dart landed was measured by the experimenter, and the observers were given no feedback about their performance.

Following each series of experimental trials, the observer’s phoria was measured while fixating an LED positioned on the target. A Maddox rod and a variable dioptre prism were used to measure phoria. When measuring phoria of the right eye, the observer first positioned the variable dioptre prism in front of this eye. S/he then fixated the light source and adjusted the variable prism until the vertical line seen with the right eye and the light source seen with the left eye were superimposed.

Observers

Seven observers (three male and four female) who had normal vision or used contact lenses for correction participated.

Results and Discussion

Precision

The observers threw the darts more precisely in the binocular condition than in the monocular conditions. The mean variable errors (i.e., mean standard deviations), across the seven observers, in the binocular, the left eye, and the right eye conditions were 7.47, 8.96, and 7.70 cm, respectively. A one-way repeated-measures ANOVA performed on these data revealed a significant difference $F(2,12) = 4.10$, $p < .05$, $\eta^2 = 0.41$. Tukey's HSD test revealed that the only significant difference was that between the binocular and the left eye conditions, HSD = 1.48, $p < .05$.

Accuracy

The observers threw the darts very accurately in the binocular viewing condition and inaccurately in the monocular viewing conditions. The mean constant error, across the seven observers, in the binocular condition was -0.23 cm (the negative sign denotes that, on average, the darts landed to the left of the intended target). In the monocular conditions, the average constant error was -2.01 cm when viewing with the left eye and 1.48 cm when viewing with the right eye. We compared the mean constant error in the monocular conditions (left and right eye conditions combined) to the constant error in the binocular condition using a Wilcoxon signed-ranks test. This analysis revealed that the constant errors in the binocular condition were significantly smaller than those in the monocular conditions, $T = 1$, $p < .025$. We did not perform an ANOVA on these data because the assumption of homogeneity of variance was violated (Ferguson, 1966). The between-subject variances in the binocular, the left eye, and the right eye conditions were 2.72, 27.79, and 20.61, respectively. Both monocular condition variances were significantly larger than the binocular condition variance, $t(5) = -3.73$, $p < .02$ for the binocular vs. left eye conditions, and $t(5) = -3.07$, $p < .05$ for the binocular vs. right eye conditions. These large between-subject variances in the monocular conditions are a direct consequence of individual differences in the magnitude of phoria and the lower precision in the monocular conditions.

Averaged across the seven observers the mean phoria (standard deviation) was -1.34 dioptres (2.41). The negative sign indicates that, on average, the observers were esophoric. This means that when fixating the target with one eye, the occluded eye was overconverged (i.e., the visual axes intersected in front of the target), and as a result the target should appear displaced away from the occluded eye (see Figure 5.1). Of the seven observers six were esophoric and one was exophoric. For the exophoric observer, when she was fixating the target with one eye, her occluded eye was underconverged (i.e. the visual axes intersected behind the target), and as a result the target should appear displaced towards the occluded eye (see Figure 5.1). Additionally, there was a fair amount of individual differences in the magnitudes of the phoria (range -5.87 to 2.15 dioptres), which means there should also be a fair amount of individual differences in the magnitudes of the mislocalization of the target.

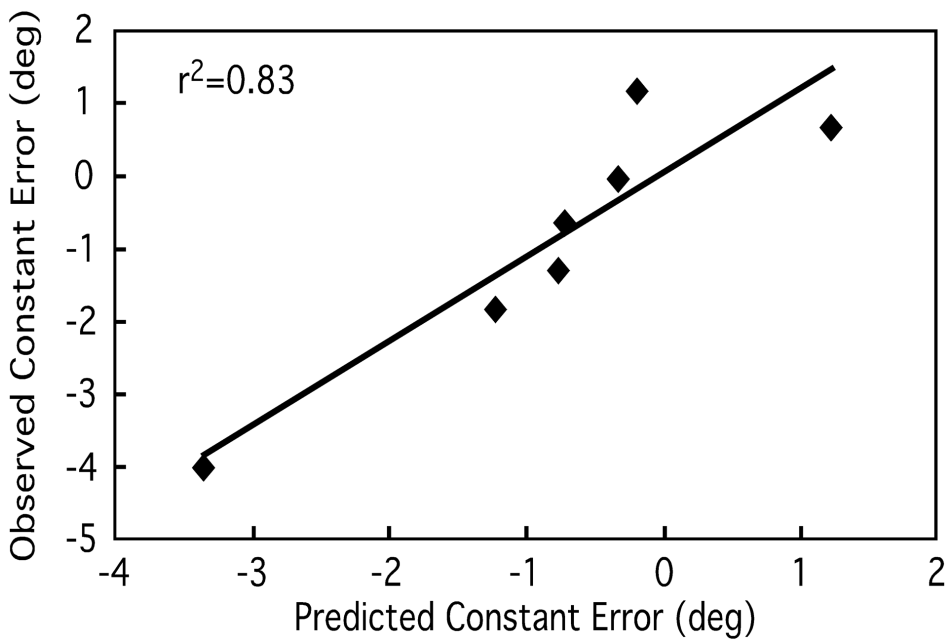

Figure 5.2. Predicted and observed constant errors of dart throws while viewing the target monocularly. Negative signs indicate a deviation toward the seeing eye.

Figure 5.2 shows a plot of the obtained constant errors vs. the predicted constant errors for the seven observers in the monocular viewing conditions. The data from the left eye and the right eye conditions were combined by subtracting errors in the right eye condition from those in the left eye condition. The predicted constant errors were calculated based on the laws of visual direction and the measured phoria value for each of the observers. As the figure clearly shows, the obtained constant errors closely match the errors predicted by the laws, $r(5) = 0.91$, $p < .01$.

Experiment 2

The dart-throwing task performed in experiment 1 was an absolute direction task: to perform the task, observers had to judge the direction of the target with respect to themselves before throwing the dart. Shooting a pistol is also an absolute direction task, if one aims the pistol without aligning the barrel to either eye. In contrast, shooting a rifle is a relative direction task; to hit the target with a rifle, one judges the relative direction of the target with respect to the two sights. If the sights of the rifle are “true” and the visual alignment of the target and the two sights is kept while pulling the trigger, the target will be hit. As argued elsewhere (Ono, Mapp, & Howard, 2002), the apparent location (i.e., absolute direction) of the target, when shooting a rifle as described above, is irrelevant as to whether the target would be hit. Comparing the results from these two situations (aiming a rifle versus aiming a pistol) is a useful way of demonstrating the difference between relative and absolute visual directions. In experiment 2 we combined a relative direction task (pointing a seen rifle at a target) with an absolute direction task (pointing an unseen pistol at the same target). We examined the accuracy and precision of both tasks. For the relative direction task, we measured the accuracy and precision of aiming a rifle at a target while monocularly focusing on the near sight, the far sight, or the target. For the absolute visual direction task, we measured the accuracy and precision of aiming a pistol at a target while the two sights (near and far) of the rifle were visually aligned with the target. The pistol was aimed while focusing on the near sight or far sight of the rifle monocularly, or while focusing on the target monocularly or binocularly. Our predictions were similar to the ones made in experiment 1. First, precision in the rifle-aiming task would be higher than that in the pistol-aiming task. Second, the pistol-aiming task would be performed inaccurately during monocular but not binocular fixation conditions. Third, the magnitude of this inaccuracy would be related to the observer's convergence and phoria at the given fixation distance. Fourth, the mean standard deviation of the aiming errors in the binocular conditions would be smaller than in the monocular conditions.

Method

Apparatus

Figure 5.3 shows the apparatus used in experiment 2. The apparatus consisted of two horizontal panels, positioned at heights of 85 cm and 134 cm; other components were attached to these panels as follows. A pistol-shaped laser pointer (pistol) was attached to the bottom panel. The pistol was fixed to one end of a metal beam; the other end of the beam was attached to the shaft of a rotary potentiometer via a gear system. The pistol-beam tandem could rotate together with the shaft of the potentiometer. Rotating the pistol changed the resistance of the potentiometer. The angular position of the pistol was determined by measuring the resistance of the potentiometer with an ohmmeter and later converting it to degrees. The rifle was attached to the top panel of the apparatus via a swivel and a slide. This allowed a wide range of lateral and angular movement of the rifle. A pair of green miniature LEDs formed the sights of the rifle. When aligned with an observer's eye, the distance from the eye to the near sight was 33cm and that to the far sight was 67cm. The sights were vertically separated so that both were visible to the observer when aiming the rifle. A laser pointer was attached to the front of the rifle (not seen in Figure 5.3). This pointer was used to check the alignment of the rifle sights with the target (see Procedure). A nose groove was cut in the top panel to help stabilize the observer's head.

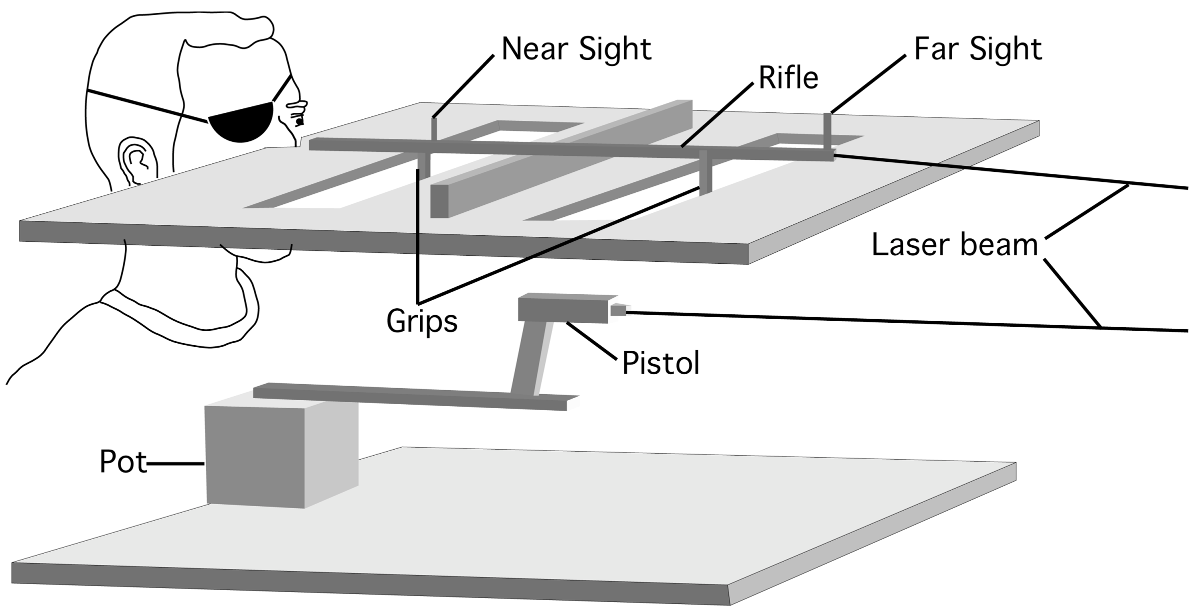

Figure 5.3. Illustration of the apparatus used in Experiment 2.

In addition to the items shown in Figure 5.3, a projector, positioned to the rear and above the observer, was used to project vertical lines (targets) onto a wall 242 cm in front of the observer. Each of the target lines was approximately 8 mm wide. The 12 possible target locations covered a span of approximately 24 deg (±12 deg of straight-ahead in 2 deg steps).

Procedure

The experiment was conducted in a dimly illuminated room; the only light sources were the projector and a computer monitor. Observers sat in an adjustable chair in front of the apparatus. They could see the rifle and the targets projected on the wall in front of them, but not the bottom panel, their own arms, or the pistol, all of which were occluded by the top panel.

The experiment was divided into 16 blocks, each consisting of 9 practice trials, 12 experimental trials, and 9 phoria measurements. Additionally, 24 practice trials were carried out at the start of the experiment and after every 4th block. Before each trial, the experimenter rotated the gun to one of five possible starting positions to reduce potential kinesthetic learning. During practice trials the observer fixated a target binocularly, pointed the pistol at it, and ‘fired’, (i.e., shone the laser beam). Shining the laser beam was the only way to receive feedback on one’s performance. Because the target was fixated binocularly, the rifle served no practical purpose; for this reason, observers were instructed to ignore the rifle during practice (and in binocular experimental trials, see below).

Practice trials were followed by experimental trials. During these trials the observer did not fire the pistol after pointing it at the target and hence did not receive feedback. However, the position of the pistol was recorded by the experimenter and constituted the observer's judgment of the absolute direction of the target. The difference between the actual direction of a target and the direction in which the observer's pistol pointed was defined as aiming error. Thus, we assessed the perceived absolute direction of a target by measuring the aiming error.

There were four fixation conditions during the experimental trials: (a) *binocular*, in which the observer maintained binocular fixation on the target while pointing the pistol at it, (b) *monocular near*, in which the observer maintained monocular fixation on the near sight of the rifle while aligning both sights with the target and pointing the pistol at it, (c) *monocular far*, in which the observer maintained monocular fixation on the far sight of the rifle while aligning both sights with the target and pointing the gun at it, and (d) *monocular target*, in which the observer maintained monocular fixation of the target while aligning both sights of the rifle with it and pointing the pistol at it. The observer wore an eye patch over the left or right eye during the monocular fixation conditions (b-d).

To align the rifle with the target in the monocular fixation conditions (b-d), the observer moved the rifle until the near sight, the far sight, and the target were vertically aligned. The experimenter checked this alignment by briefly turning on the laser pointer positioned at the front of the rifle. Observers were unable to see the laser beam, because it was occluded by the top horizontal panel. Aligning the sights with the target constituted the observer's judgment of relative direction of the target.

At the end of each block of experimental trials, the observer's phoria was measured at three viewing distances: (a) near sight (33 cm from the observer), (b) far sight (67cm from the observer), and (c) target fixation, where an LED was placed on the wall (242 cm from the observer). A Maddox rod and a variable dioptre prism were used to measure phoria. When measuring phoria of the right eye, the observer first positioned the variable dioptre prism in front of this eye. S/he then fixated the light source and adjusted the variable prism until the vertical line seen with the right eye and the light source seen with the left eye were superimposed.

Three of 12 targets were presented during any one block. Twelve experimental trials were necessary to display all four fixation conditions for each of three targets while keeping the same eye occluded. Eight blocks were necessary to present each of four fixation conditions for each of 12 targets to each eye. A total of 16 blocks were conducted for each observer. The order of target presentation and fixation conditions was randomized.

Observers

Ten observers participated in this experiment. All were naïve to the purpose of the experiment. They were paid for participating.

Results and Discussion

Relative Direction: Accuracy and Precision.

All 10 observers performed highly accurately and precisely in the relative direction task (i.e., the rifle aiming task). Of the total 1440 trials run across the ten observers there was only one instance in which the laser beam (0.20 deg in diameter) did not overlap with the target line (0.19 deg in width). This result is not surprising given that aligning the sights with the target is essentially a Vernier acuity task, which is known to be performed with high accuracy and precision (See e.g., Ludvigh, 1953; Westheimer & McKee, 1977).

Absolute Direction: Accuracy

For all analyses aiming error data from the 12 target locations were averaged. For the absolute direction task (i.e., the pistol shooting task) we performed three separate analyses. In the first analysis we compared aiming errors while fixating the target binocularly, with the left eye only, and with the right eye only. Since phoria affects only the monocular absolute direction judgments, it was expected that the monocular errors would be larger than the binocular errors. In the second analysis we compared aiming errors while fixating the target, the far sight, and the near sight monocularly. Since phoria was expected to be largest in the near sight fixation condition, intermediate in the far sight fixation condition, and smallest in the target fixation condition, it was expected that the magnitude of absolute direction errors would vary in the same way. In the final analysis we compared the observed absolute direction errors in the monocular fixation conditions to those predicted by the laws of visual direction and the magnitude of each of the individual observers' phorias. If absolute direction is processed as specified by the laws, we should find a linear relationship between the observed and the predicted errors.

For the first analysis we performed a one-way repeated-measures ANOVA with three factors (binocular fixation, left eye fixation, and right eye fixation). For this analysis, aiming errors to the right of the target were coded as positive and those to left of the target were coded as negative. Averaged across the ten observers the mean errors (standard deviations) in the binocular, the left eye, and the right eye fixation conditions were 0.77 deg (0.68), -1.12 deg (0.68), and 1.99 deg (1.31), respectively. The ANOVA revealed a significant difference, $F(2, 18) = 39.99$, $p < .0001$, $\eta^2 = 0.82$. Tukey's HSD test revealed that all mean differences between the conditions were significant, HSD = 1.162, $p < .01$.

For the second analysis we performed a one-way repeated-measures ANOVA with three monocular fixation factors (target, far sight, and near sight). For this analysis, aiming errors to the outside of the target (i.e., to the temporal side of the viewing eye) were coded as positive and those to inside of the target (i.e., to the nasal side of the viewing eye) were coded as negative. Averaged across the 10 observers the mean errors (standard deviations) in the target, the far sight, and the near sight fixation conditions were 1.55 deg (0.57), 1.79 deg (0.39), and 2.63 deg (0.61), respectively. The ANOVA revealed a significant difference, $F (2, 18) = 16.71$, $p < .0001$, $\eta^2 = 0.65$. Tukey's HSD test revealed significant differences between the target and the near sight fixation conditions and between the far sight and the near sight fixation conditions, HSD = 0.653, $p < .01$. No significant difference was found between the target and the far sight fixation conditions.

Averaged across the 10 observers the mean phorias (standard deviations) while monocularly fixating the target, the far sight, and the near sight were 1.04 (1.52), 4.44 (2.27), and 8.36 (3.80) dioptres, respectively. On average the observers were exophoric at all fixation distances and the magnitude of the phoria increased as fixation distance decreased. (The LED used to measure phoria at the target distance produced exophoria instead of esophoria as in experiment 1. In experiment 2, the LED had to be placed higher than the far sight to be visible to the observer. This exophoria was due to the LED requiring an eye elevation of about 5.5 degree. See Heuer and Owens (1989) for divergence caused by an eye elevation.)

Based on fixation distance and on each individual observer's phoria we computed the expected magnitude of mislocalization of the target as predicted from the laws of visual direction. (See Figure 5.4 for an explanation of the expected mislocalization.) Presented in Figure 5.5 are the predicted constant errors plotted against the obtained constant errors. Each point on the graph is the data from one observer. The circles represent data from the target fixation condition, the triangles represent the far sight fixation condition, and the squares the near sight fixation condition. The overall correlation between the obtained and predicted constant errors across the three monocular fixation conditions was $r(28) = +0.70$. We could not test the significance of this value directly, because the data points across the three fixation conditions were not independent. Therefore, to test for significance we calculated individual correlations of obtained vs. predicted constant errors across the three fixation conditions for each observer, and then performed a single sample t-test on those values to determine if they differ significantly from zero. The mean correlation across the ten observers was +0.82 with a standard deviation of 0.29. This mean correlation was significantly different from zero, $t(9) = 8.86$, $p < .0001$ and the effect size was large, $r^2 = 0.90$. As with experiment 1, this is strong evidence in support of the idea that the visual system processes absolute direction in the manner specified by the laws of visual direction.

Absolute Direction: Precision

As expected, and consistent with experiment 1, the observers aimed the pistol more precisely in the binocular condition that in the monocular conditions. The mean variable errors (i.e., mean standard deviations), across the 10 observers, while fixating the target binocularly, with the left eye only, and with the right eye only were 2.05, 2.46, and 2.36 cm, respectively. A one-way repeated-measures ANOVA performed on these data revealed a significant difference $F(2,18) = 8.21$, $p < .05$, $\eta^2 = 0.48$. Tukey's HSD test revealed significant differences between the binocular and the left eye only fixation conditions, HSD = 0.35, $p < .01$ and between the binocular and the right eye only fixation conditions, HSD = 0.27, $p < .05$. No significant difference was found between the left eye only and the right eye only fixation conditions.

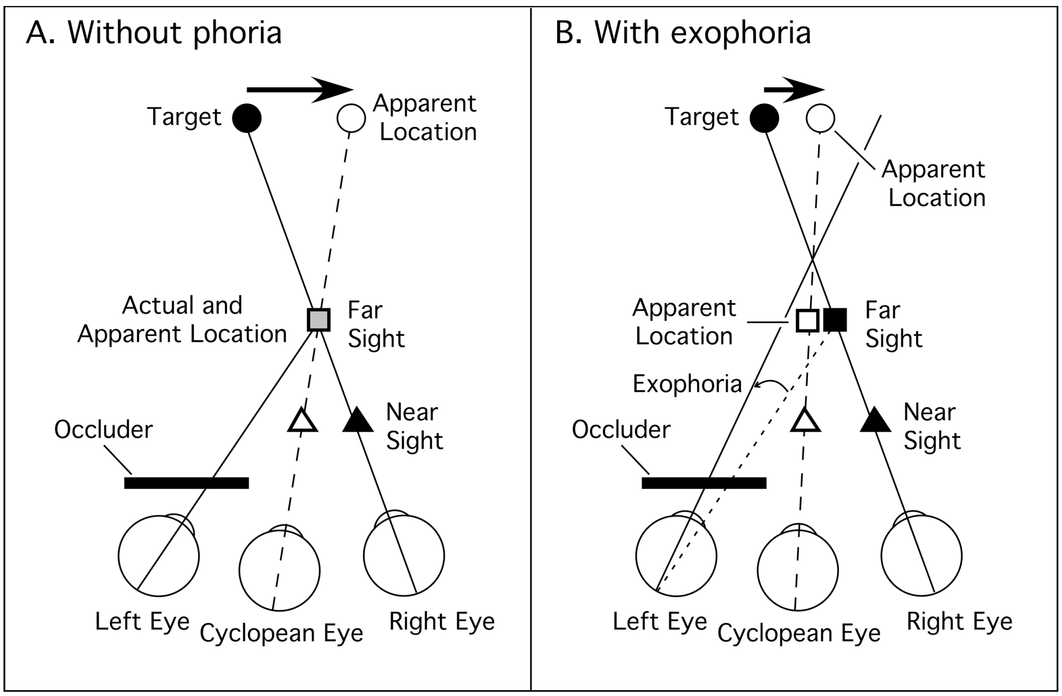

Figure 5.4. Illustration of the apparent location of a target as predicted by the laws of visual direction. (A) shows the prediction without phoria when the far sight is accommodated. The target appears shifted toward the seeing eye. (B) shows the prediction with exophoria. The predicted constant error is a function of two variables: phoria and the sight that is accommodated. As in Figure 5.1, depicted are the predicted head-centric visual directions; for the predicted torso-centric directions the visual system needs to incorporate the orientation of the head with respect to the torso.

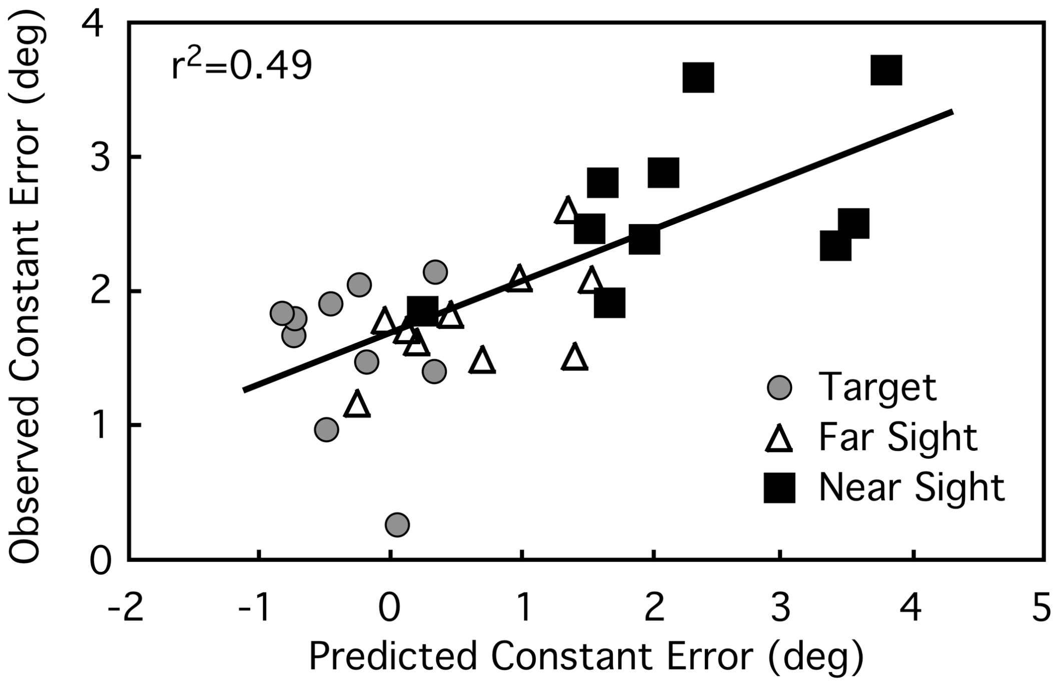

Figure 5.5. Predicted and observed constant errors of pistol aiming while accommodated to the near sight, the far sight, and the target.

General Discussion

We use the term ecological validity in reference to results from a laboratory that are generalizable to results obtained with a task that we are more likely to encounter in our daily lives (see Beber & Beber, 2001). In general, the results of this study, obtained with dart throwing, rifle aiming or pistol aiming tasks, validate the long list of studies in Mapp et al. (2003) that can be dated back to the writings of Ptolemy (c. 100-175) and of Alhazen (965–1040). Our results confirm that we perceive directions of objects as though from the midpoint between our two eyes and that this idea applies equally to both monocularly and binocularly seen stimuli. See Howard and Wade (1996) for the work by Ptolemy and see Howard (1996) for the work by Alhazen.

The results also validate the claim by Khokhotva et al. (2005) and Ono, Lillakas, and Mapp (2003) that the distinction between relative and absolute visual direction is critical in understanding visual direction. Judging whether three points (the two rifle sights and the target) are collinear or not is a different task than judging the location of a point in space when aiming a dart or a pistol. The relative direction task we used was essentially a Vernier acuity task, for which judgments are known to be both accurate and precise, assuring a high proportion of correct judgments, although our criteria for a correct response was not as stringent as in the usual Vernier acuity experiment. A correct relative direction judgment does not translate into a correct absolute direction judgment, however, because only the latter is dependent upon the convergence state of the eyes. The fact that changes in convergence state, created by different magnitudes of phoria, produce predictable and reliable changes in absolute direction counters the claim by Erkelens (2000) that the visual directions of monocularly seen stimuli are specified from the viewing eye and that "perceived direction during monocular viewing is based on signals of the viewing eye only" (Erkelens, p. 2411). This is so, because the predictions are based on the laws of visual direction that postulate the centre of visual direction to be located at the midpoint between the two eyes.

These validations contrast the claim by Erkelens and van Ee (2002) that the concept of the cyclopean eye is "always irrelevant" in vision. As pointed out by Khokhotva et al. (2005), the basis of Erkelens and van Ee's conclusion regarding monocular visual direction likely resulted from their not making a distinction between relative and absolute visual direction and from focusing only on relative visual direction.[12] In partial agreement with their claim, we acknowledge that the concept of the cyclopean eye need not be invoked for a relative visual direction task in which the stimuli are at the same distance, or for a task in which adaptation to an apparent displacement is measured by pointing with unseen hand to a stimulus at a fixed pre-post adaptation

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[12] However, we do not understand the basis of Erkelens and van Ee's (2002) argument that the concept of a cyclopean is relevant for motor tasks but not for visual tasks. In making the case for this distinction, they appear to be saying that what appears straight-ahead before wearing a prism still appears straight-ahead after wearing it, and the pointing error after wearing a prism is explained as "the finger movements are not correctly calibrated to the perceived direction" (page 116). The opposite is true, however, because the finger movement is calibrated to the *visual direction* (not to the actual direction), and therefore the pointing error is made. All the visual stimuli including that of the straight-ahead are perceptually displaced from the actual direction. See Ono et al. (1983) for a discussion of visual direction while wearing a prism.

distance.[13] For these stimulus situations, it is not possible to determine experimentally whether the directions are seen from the cyclopean eye or from the viewing eye. Moreover, invoking the concept does not contribute to the understanding of the processes involved in these situations, although a case can be made that visual direction is always specified with respect to the cyclopean eye. The concept does need to be invoked to explain results from an experiment that requires processing either (a) the relative direction of two or more stimuli located at different distances or (b) the absolute direction of a stimulus with respect to the observer. The judgment of colinearity in experiment 2 is made when the line passing through the two sights of the rifle and the target points to the viewing eye but appears to point to the cyclopean eye. For recent evidence for this claim, see Khokhotva et al.; for a recent review of historical evidence, see Mapp et al. (2002) and Wade, Ono, and Mapp (2006). The motor response required in throwing the dart in experiment 1, or aiming the pistol in experiment 2, cannot be made until the absolute visual direction of the intended target is processed.

Finally, regarding Erkelens and van Ee's (2002) claim that the body of literature that supports the concept of a cyclopean eye is based on poorly conducted experiments, they have neither specified which experiments nor what aspects of the experiments are poor. Wade et al. (2006) have recently examined the work on visual direction from 1792 to 1897 and found that the stimuli used by Wells (1792), Towne (1865, 1866, 1869, 1870) and LeConte (1881, 1897) were carefully prepared, and the experiments were

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[13] For adaptation studies that require the concept of the cyclopean eye, see Ono and Angus (1974); Ono and Weber (1981).

carefully conducted with respect to controlling eye position. Moreover, the conclusions regarding visual direction that they reached remain valid today.

Appendix

We viewed videotapes of professional dart throwers to determine if they were performing a relative or an absolute direction task. Dart throwing tournaments televised by the Ontario Sports Network (now defunct) on July 2001 and January 2002 were recorded and examined. The tournament recorded on July 2001 had 4 competitors (2 females and 2 males), while that recorded on January 2002 had 2 competitors, both of which were male. Each match had 2 competitors of the same gender (i.e., female versus female, and male versus male) and the competitors threw three darts for each round. As they threw their darts, the camera angle showed either a frontal view or a side view of the competitors' upper body. The movement of the competitors' arms and eyes were analysed from both of these views and inferences about the visual direction task they were employing while performing the dart-throwing task were made based on these observations.

All six of the professional dart throwers threw darts with both eyes open and with their eyes fixated on the target. Moreover, all six appeared to be performing an absolute direction task. Four of them threw the dart from the side of their faces, which prevented them from seeing the dart and using it as a reference point to perform a relative direction task; while, the other two threw the dart from the front of their faces, however, they did not appear to be performing a relative direction task because they did not attempt to align the target and the dart with either eye.

Chapter Six: Summary and Conclusion

6.1 Summary

The seven experiments presented in this dissertation were designed to measure the accuracy and precision of absolute and relative direction judgments under monocular and binocular viewing conditions. The purpose of the experiments was to assess the validity of several claims in the literature that the cyclopean eye is not fixed in the head, but moves along the interocular axis as a function of the stimulus situation and the eye(s) used to view the stimuli (Erkelens, 2000; Erkelens & van de Grind, 1994; Erkelens, Muijs, & van Ee, 1996; Khan & Crawford, 2001; Mansfield & Legge, 1996, 1997). The results of the experiments refute these claims and elucidate which types of visual direction tasks can and cannot be used to specify the location of the cyclopean eye.

The common factor in the studies listed above is that all the claims about the location of the cyclopean eye are based on relative direction judgments only. As clearly shown in this dissertation, relative direction judgments are extremely accurate and precise (see Chapter 5, Experiment 2) but, in and of themselves, they are not sufficient to infer the location of the cyclopean eye. Absolute direction judgments such as those in Chapter 3, Experiment 1, and Chapter 5, Experiments 1 and 2 are required. These experiments showed that objects situated at different distances along the visual axis of an eye appear aligned (i.e., in the same relative direction), but they do not appear aligned to the viewing eye. They appear aligned to the point midway between the two eyes, the cyclopean eye, and this can only be determined via an absolute direction judgement. Moreover, alternating fixation between the near and far stimuli does not alter the relative direction of the stimuli, but it does alter the absolute direction of the stimuli (i.e., it produces the cyclopean illusion).

The conditions under which the cyclopean illusion occur were examined in Chapter 3, Experiment 2 and Chapter 4, Experiments 1, 2 and 3. These experiments showed that the cyclopean illusion occurs under both binocular (disparity vergence) and monocular (accommodative vergence) conditions, provided the vergence eye movements are not too small. This held for both real stimuli and afterimages, provided neither were located at the intersection of the visual axes. These findings confirm that absolute direction of visual targets is based on binocular eye position, independent of whether the stimuli are viewed binocularly or monocularly.

The importance of binocular eye position on both binocular and monocular absolute direction judgments was further examined in the two experiments in Chapter 5. Using more ecologically valid stimulus situations (dart throwing and rifle and pistol aiming), the results from these two experiments showed that binocular absolute direction judgments are accurate. Monocular absolute direction judgments of the same targets, however, are inaccurate, and the magnitude and direction of the inaccuracies are predictable from the inaccuracies in convergence angle (binocular eye position) resulting from the phoria associated with monocular fixation. These findings confirm and expand the generalizability of previous findings from traditional LED in the dark type experiments.

In summary, the results from the seven experiments reported here clearly show that monocular relative direction judgments are highly accurate and precise, are independent of binocular eye position, and cannot be used as the basis from which to infer the position of the cyclopean eye. Absolute direction judgments, on the other hand, are less precise than relative direction judgments and the accuracy of both monocular and binocular absolute direction judgments is dependent upon binocular eye position. When the eyes converge accurately on the target of interest, absolute direction judgments are accurate. When the eyes converge inaccurately on the target of interest, which is often the case during monocular fixation, absolute direction judgments are inaccurate.

6.2 Limitations

An important part of the research process involves considering how methodology limitations may impact the obtained results. Such a process helps to delimit the generalizability of the results and may suggest directions for future research. The purpose of this section is to address limitations in the present research.

In Chapters 3 and 4, measures of absolute direction were obtained by asking observers to report (a) the location of the near LED with respect to their face (e.g., in front of the nose, in front of the eye, or between the eye and the nose and by how much) and (b) the part of their face to which the imaginary line connecting all three LEDS appeared to point. In these experiments, the stimuli were always presented on the visual axis of one of the eyes and no attempt was made to conceal this from the observers. Therefore, it is possible that the observers' knowledge of the actual locations of the stimuli, and the eye to which they were presented, may have influenced their reports of where the stimuli appeared with respect to their face. Despite this knowledge, however, the observers overwhelmingly reported that the stimuli appeared aligned with their nose. This result is consistent with the hypothesis that stimuli on a visual axis transfer to the common axis with monocular viewing. There were a few rare instances (one or two observers on one or two trials), however, when observers reported that the stimuli appeared aligned to the viewing eye. Although it is likely that these rare instances were due to the observers' knowledge of the stimuli locations interfering with their reported percepts, this cannot be confirmed with the experiments reported here. An experiment by Khokhotva et al. (2005) in which observers made absolute direction judgments similar to the ones reported here, but without knowledge of which eye was viewing the targets or the targets' actual locations, support the idea that knowledge occasionally interfered with perception.

Also measured in the experiments reported in Chapters 3 and 4 was the occurrence and magnitude of the cyclopean illusion with binocular and monocular viewing. As stated above, one of the main results of these experiments is that the cyclopean illusion occurs under both binocular (disparity vergence) and monocular (accommodative vergence) conditions, provided the vergence eye movements are not too small. This result is also consistent with the hypothesis that absolute direction with both binocular and monocular viewing is based on the oculomotor signals from both eyes. The generalizability of the reported magnitudes of the illusion, particularly in the binocular conditions may be limited, however. Observers in these experiments were not screened for stereoacuity. It is possible that the eye movements of observers with poor stereoacuity differ from those with good stereoacuity in the binocular (disparity vergence) conditions, which would affect the magnitude of the illusion. Although there is no way to know if stereoacuity affected the magnitude of the illusion in the binocular conditions of the reported experiments, it certainly did not eliminate the illusion. All observers experienced the illusion in all of the binocular conditions and the magnitude of the illusion was consistently larger than in the comparable monocular conditions.

As mentioned in Chapter 1, fixation disparity is the slight deviation of the visual axes from the intended point of convergence when both eyes are open. As a result of fixation disparity, a binocularly fixated target falls on slightly disparate points in the two retinas. The disparity is not so large as to cause diplopia and the absolute direction of the target is based on the average of the oculocentric components in the two eyes and binocular eye position (Ono et al., 1977). Fixation disparity can be measured or monitored with either objective or subjective measurements (Kertesz & Lee, 1987; Remole, 1983, 1984, 1985). It was neither measured nor monitored in any of the experiments reported here. Although it is unlikely that fixation disparity altered the results in any appreciable way, its effect remains unknown. If the direction of any fixation disparity in the binocular conditions were the same as the phoria in the monocular conditions, then it may have slightly decreased the magnitude of the cyclopean illusion in those binocular conditions. Alternatively, if the direction of any fixation disparity in the binocular conditions were unrelated to the direction of phoria in the monocular conditions, then it may have added variability to the binocular absolute direction judgements.

In the experiments in Chapters 3 and 5, phoria was measured with a Maddox rod and a variable dioptre prism. It was measured in the dark, at the end of the experimental sessions and the fixation stimulus, disassociated for the two eyes by the Maddox rod placed over one eye, was a continuously illuminated LED. As discussed in Chapter 3, the phoria values were used as the measure of the imperfect coupling of accommodation and vergence in the monocular conditions of the cyclopean illusion experiment. The phoria results from that experiment are consistent with the hypothesis that the rarity of the monocular cyclopean illusion was due, in part, to the lack of sufficiently large eye movements (see Figure 3.6). In Chapter 5, the measured phoria values for each observer were used to predict constant errors in the absolute direction of monocularly viewed targets, from the laws of visual direction. The results from those experiments showed that the obtained constant errors closely matched the constant errors predicted from the phoria measures (see Figures 5.2 and 5.5). It is important to note that phoria values have been reported to vary as a function of measurement method (Schroeder, Rainey, Goss, & Grosvenor, 1996), age (Freier & Pickwell, 1983), and periods of sustained fixation (Alvarez, Kim, Yaramothu, & Granger-Donetti, 2017). In the experiments reported here a single phoria measurement method was used throughout, and potential effects of age or sustained fixation were not examined. It is possible, therefore, that the phoria values may have differed if they were measured using a different method, age of observer, or period of fixation, then used here. The link between phoria and the reduction in the magnitude of eye movements with monocular viewing, or the inaccuracies in absolute direction judgments of monocularly viewed targets resulting from phoria, however, would likely remain unchanged.

Lastly, in Chapter 5 a pistol aiming task and a dart throwing task was used to test the hypothesis that the accuracy of absolute direction judgements, with monocular viewing, is dependent upon binocular eye position. The obtained results overwhelmingly support the hypothesis. The pistol aiming task, however, lacked complete ‘real-world’ authenticity. To measure the angular position of the simulated pistol it was attached to a potentiometer via a metal beam, which restricted its range of motion. To ensure that the pistol aiming was performed as an absolute direction task, the simulated pistol was aimed out of sight of the observer. This measurement restriction and experimental control lessened the desired ecological validity of the task.

6.3 Conclusion

The above limitations notwithstanding, the research presented in this dissertation advances our understanding of how visual directions specified from the cyclopean eye located midway between the eyes (perceptual variables) are derived from the inputs from the two eyes (physical variables). Critical to this understanding is the distinction between absolute and relative direction. The research presented here has shown that this distinction is sometimes confused or not made explicit, which has led to controversies in the visual direction literature. For example, recurring claims about the location, stability, and relevance of the cyclopean eye have been made in the literature, based solely on relative direction tasks (e.g., Erkelens, 2000; Erkelens & van de Grind, 1994; Erkelens et al., 1996; Khan & Crawford, 2001; Mansfield & Legge, 1996, 1997; Parson, 1924; Porac & Coren, 1981; Rubin & Walls, 1969; Sheard, 1926; Walls, 1951). The data and arguments presented in this dissertation show that such claims can only be made based on absolute direction tasks. Perhaps the lack of an explicit distinction between absolute and relative direction in Wells (1792), Hering (1879/1942) or in what Ono and Mapp (1995) called Wells-Hering's laws of visual direction contributed to some of the controversies over the relevance of the cyclopean eye. The clear, explicit distinction between absolute and relative direction presented here will help to prevent the occurrence of similar controversies in the future.

In addition to the distinction between absolute and relative direction discussed above, another important contribution of the present research is that it extends our knowledge of how the absolute directions of monocular targets are derived. The data presented here show that it is the angular positions of both eyes, not just the eye that happens to be open or viewing the target, that is combined with the target's retinal image location to determine absolute direction.

Lastly, as discussed above, the concept of the cyclopean eye has been challenged from time to time. The results from the experiments reported here, however, confirm the relevance and the necessity of the concept. It is necessary, for example, to explain the cyclopean illusion. This is not to say that its purpose is to produce the cyclopean illusion, but rather the illusion is a consequence of the way in which the information from the two eyes (retinal image location and binocular eye position) is combined to yield a percept of where visual objects appear with respect to ourselves. Sometimes these percepts are inaccurate, but these inaccuracies inform us about the relevant underlying processes.

Glossary

Absolute direction The visual direction of an object with respect to ourselves. Synonymous with egocentric direction.

AC/A ratio The amount of accommodative convergence (AC), measured in prism dioptres evoked by a one dioptre change in accommodation (A).

Cyclopean eye The origin or centre in the head from which visual direction judgments are made. Synonymous with egocentre, projection centre, and the centre of visual direction.

Cyclopean illusion The apparent lateral shift of stationary stimuli on a visual axis that occurs when vergence changes from one of the stimuli to the other. See Figure 1.6.

Esophoria A phoria (see definition below) in the direction of increased convergence. See Figure 5.1.

Exophoria A phoria (see definition below) in the direction of decreased convergence. See Figure 5.1.

Fixation disparity A slight deviation of the visual axes from the intended point of convergence when both eyes are open. The deviation is too small to cause the fixated target to be seen as double.

Horopter The locus of single points in space, each of which project to corresponding points on the two retinas. Typically, it is a circle (the Vieth-Müller circle) passing through the point of binocular fixation and the nodal point of each eye.

Nodal point The point in the lens where all visual lines intersect. Strictly speaking any lens system has two nodal points; an anterior and a posterior. For most purposes, we may consider these two points to coincide at a single point on the visual axis of the human eye, approximately 17 mm in front of the retina and 6 mm in front of the centre of rotation.

Phoria "The direction or orientation of one eye, …in relation to the other eye, manifested in the absence of an adequate fusion stimulus…" (Cline, Hofstetter, & Griffin, 1989, p. 529)

Relative direction The visual direction of an object with respect to another object in the visual field. Synonymous with exocentric direction.

Vergence A disjunctive rotational movement of the eyes in which the rotations of the two eyes are equal in magnitude but opposite in direction. Horizontal vergence movements involve rotations of both eyes inwards towards the nose (convergence) or outwards towards the temples (divergence).

Version A conjunctive rotational movement of the eyes in which the rotations of the two eyes are equal in magnitude and direction.

Visual axis The visual line(see definition below) through the centre of the fovea.

Visual line Any straight line passing through the pupil and the nodal point of an eye. A visual line is the locus of all points, fixed relative to the eye, which stimulate a given point on the retina.

References

Aggarwala, K. R., Nowbotsing, S., & Kruger, P. B. (1995). Accommodation to monochromatic and white targets. *Investigative Ophthalmology and Vision Science, 36,* 2695-2705.

Alhazen, I. (1989). *Book of optics, in The optics of Ibn al–Haytham two volumes.* (A. I. Sabra, Trans.). London: Warburg Institute. (Original work published 1083)

Alpern, M., & Ellen, P. (1956). A quantitative analysis of the horizontal movements of the eyes in the experiment of Johannes Mueller – I. Methods and results. *American Journal of Ophthalmology, 42,* 289-296. doi:10.1016/0002-9394(56)90380-4

Alvarez, T. L., Kim, E. H., Yaramothu, C., & Granger-Donetti, B. (2017). The influence of age on adaptation of disparity vergence and phoria. *Vision Research, 133,* 1–11. doi: 10.1016/j.visres.2017.01.002

Banks, M. S., van Ee, R., & Backus, B. T. (1997). The computation of binocular visual direction: A re–examination of Mansfield and Legge (1996). *Vision Research, 37,* 1605–1610.

Barbeito, R. (1981). Sighting dominance: An explanation based on the processing of visual direction in tests of sighting dominance. *Vision Research, 21,* 855–860. doi:10.1016/0042-6989(81)90185-1

Barbeito, R. (1983). Sighting from the cyclopean eye: The cyclops effect in preschool children. *Perception & Psychophysics, 33*, 561–564. doi:10.3758/BF03202937

Barbeito, R., & Ono, H. (1979). Four methods of locating the egocenter: A comparison of their predictive validities and reliabilities. *Behavior Research Methods and Instrumentation, 11,* 31-36. doi:10.3758/BF03205428

Barbeito, R., & Simpson, T. L. (1991). The relationship between eye position and egocentric visual direction. *Perception & Psychophysics, 50,* 373–-382. doi:10.3758/BF03212230

Beber, A. S., & Beber, E. (2001). *The Penguin dictionary of Psychology (3rd ed.).* London: Penguin Group.

Blake, R., & Cormack, R. H. (1979). On utrocular discrimination. *Perception & Psychophysics, 26,* 53-68. doi:10.3758/BF03199861

Brenner, E., & Cornelissen, F. W. (2000). Separate simultaneous processing of egocentric and relative positions. *Vision Research, 40,* 2557–2563. doi:10.1016/S0042-6989(00)00142-5

Bridgman, P. W. (1927). *The logic of modern physics*. New York, NY: Crowell-Collier-Macmillan.

Briggs, W. (1676). *Ophthalmographia*. Cambridge: J. Hayes.

Carpenter, R. H. S. (1988). *Movement of the eyes.* London: Pion.

Church, J. (1966.) *Language and the discovery of reality.* New York, NY: Vintage Press.

Cline, D., Hofstetter, H. W., & Griffin, J. R. (Eds.). (1989). *Dictionary of visual science. (4th ed.).* Radnor, PA: Chilton Trade Book Publishing.

Cumming, B. G., & Judge, S. J. (1986). Disparity–induced and blur–induced convergence eye movement and accommodation in monkey. *Journal of Neurophysiology, 55,* 896–914. doi:10.1152/jn.1986.55.5.896

Davies, P. (1973). Effects of movements on the appearance and duration of a prolong visual after image. *Perception, 2,* 147–153. doi:10.1068/p020147

Dengis, C. A., Simpson, T. L., Steinbach, M. J., & Ono, H. (1998). The cyclops effect in adults: sighting without visual feedback. *Vision Research, 38,* 327–331. doi:10.1016/S0042-6989(97)00157-0

Dengis, C. A., Steinbach, M. J., Goltz, H., & Stager, C. (1993). Visual alignment from the midline: a declining developmental trend in normal, strabismic, and monocularly enucleated children. *Journal of Pediatric Ophthalmology & Strabismus, 30,* 323–326.

Dengis, C. A., Steinbach, M. J., Ono, H., & Gunther, L. N. (1997). Learning to wink voluntarily and to master monocular tasks: a comparison of normal versus strabismic children. *Binocular Vision, 12,* 113-118.

Dengis, C. A., Steinbach, M. J., Ono, H., Gunther, L. N., Fanfarillo, R., Steeves, J. K. E., & Postiglione, S. (1996). Learning to look with one eye: the use of head turn by normals and strabismics. *Vision Research, 36,* 3237-3242. doi:10.1016/0042-6989(96)00026-0

DiScenna, A. O., Das, V., Zivotofsky, A. Z., Seidman, S. H., & Leigh, R. J. (1995). Evaluation of a video tracking device for measurement of horizontal and vertical eye rotations during locomotion. *Journal of Neuroscience Methods,* 58, 89–94. doi:10.1016/0165-0270(94)00162-A

Duncker, K. (1935). Über induzierte Bewegung (Ein Beitrag zur Theorie optisch wahrgenommener Bewegung). *Psychologische Forschung, 12,* 180-259. Abridged and translated as “Induced motion”. In W. D. Ellis (Ed. & Trans.), *Source book of Gestalt Psychology* (pp 161-172). London: Routledge and Kegan Paul. (Original work published 1929)

Enright, J. T. (1988). The cyclopean eye and its implications: vergence state and visual direction. *Vision Research, 28,* 925–930. doi:10.1016/0042-6989(88)90101-0

Enright, J. T. (1992). The remarkable saccades of asymmetrical vergence. *Vision Research, 32,* 2261–2276. doi:10.1016/0042-6989(92)90090-6

Erkelens, C. J. (2000). Perceived direction during monocular viewing is based on signals of the viewing eye only. *Vision Research, 40,* 2411–2419. doi:10.1016/S0042-6989(00)00120-6

Erkelens, C. J., & Collewijn, H. (1985). Motion perception during dichoptic viewing of moving random-dot stereograms. *Vision Research, 25,* 583-588. doi:10.1016/0042-6989(85)90164-6

Erkelens, C. J., & Grind, W. A. van de. (1994). Binocular visual direction. *Vision Research, 34,* 2963–2969. doi:10.1016/0042-6989(94)90268-2

Erkelens, C. J., & Regan, D. (1986). Human ocular vergence movements induced by changing size and disparity. *Journal of Physiology, 379,* 145-169. doi:10.1113/jphysiol.1986.sp016245

Erkelens, C. J., & van Ee, R. (1997a). Capture of visual direction: an unexpected phenomenon in binocular vision. *Vision Research, 37,* 1193–1196. doi:10.1016/S0042-6989(96)00265-9

Erkelens, C. J., & van Ee, R. (1997b). Capture of the visual direction of monocular objects by adjacent binocular objects. *Vision Research, 37,* 1735–1745. doi:10.1016/S0042-6989(96)00323-9

Erkelens, C. J., & van Ee, R. (2002). The role of the cyclopean eye in vision: sometimes inappropriate, always irrelevant. *Vision Research, 42,* 1157-1163. doi:10.1016/S0042-6989(01)00280-2

Erkelens, C. J., Muijs, A. J. M., & van Ee, R. (1996). Binocular alignment in different depth planes. *Vision Research, 36,* 2141 - 2147. doi:10.1016/0042-6989(95)00268-5

Feigl, H. (1945). Operationalism and scientific method. *Psychological Review, 52,* 250-259. doi:10.1037/h0056755

Ferguson, G. A. (1966). *Statistical analysis in psychology and education (2nd ed.).* New York, NY: McGraw-Hill.

Freier, B. E., & Pickwell, L. D. (1983). Physiological exophoria. *Ophthalmic and Physiological Optics, 3,* 267–272. doi:10.1111/j.1475-1313.1983.tb00613.x

Gogel, W. C. (1965). Equidistance tendency and its consequences. *Psychological Bulletin, 64,* 153–163. doi:10.1037/h0022197

Gogel, W. C., Tietz, J. D. (1980). Relative cues and absolute distance perception. *Perception & Psychophysics, 28,* 321-328. doi:10.3758/BF03204391

González, E. G., Steinbach, M. J., Gallie, B. L., & Ono, H. (1999). Egocentric localization: Visually directed alignment to projected head landmarks in binocular and monocular observers. *Binocular Vision and Strabismus Quarterly, 14,* 127-136.

Gray, R., & Regan, D. (1998). Accuracy of estimating time to collision based on binocular and monocular information. *Vision Research, 38,* 499-512. doi:10.1016/S0042-6989(97)00230-7

Grind, W. A. van de, Erkelens, C. J., & Laan, A. C. (1995). Binocular correspondence and visual direction. *Perception, 24,* 215–235. doi:10.1068/p240215

Helmholtz, H. (1962). Treatise on physiological optics, Vol. 3. J. P. C. Southall, (Ed.). New York, NY: Dover. (Original work published 1910)

Hering, E. (1942). *Spatial sense and movements of the eye.* (C. A. Radde, Trans.). Baltimore, MD: American Academy of Optometry. (Original work published 1879)

Hering, E. (1977). *The theory of binocular vision*. B. Bridgeman & L. Stark (Eds.). (B. Bridgeman, Trans.). New York, NY: Plenum Press. (Original work published 1868)

Hermann, J. S., & Samson, C. R. (1967). Critical detection of the accommodative convergence to accommodation ratio by oculography. *Archives of Ophthalmology, 78,* 424–430. doi:10.1001/archopht.1967.00980030426004

Heuer, H., & Owens, D. A. (1989). Vertical gaze direction and the resting posture of the eyes. *Perception, 18,* 363- 377. doi:10.1068/p180363

Holland, G. (1958). Untersuchung über den Einfluss der Fixationsentfernung und der Blickrichtung auf die horizontale Heterophorie (Exo- und Esophorie). v. *Graefes Archiv für Ophthalmologie, 160,* 144-160. doi:10.1007/BF00685576

Howard, I. P. (1982). *Human visual orientation.* New York, NY: John Wiley.

Howard, I. P. (1991). Spatial vision within egocentric and exocentric frames of reference. In S.R. Ellis (Ed.), *Pictorial Communication in Virtual and Real Environment* (pp. 338-358). New York, NY: Taylor and Francis.

Howard, I. P. (1996). Alhazen’s neglected discoveries of visual phenomena. *Perception, 25,* 1203–1217. doi:10.1068/p251203

Howard, I. P., & Rogers, B. J. (1995). *Binocular vision and Stereopsis.* Oxford: Oxford University Press.

Howard, I. P., & Templeton, W. B. (1966). *Human spatial orientation.* London: Wiley.

Howard, I. P., & Wade, N. J. (1996). Ptolemy's contributions to the geometry of binocular vision. *Perception, 25,* 1189–1201. doi:10.1068/p251189

Ittelson, W. H. (1951). Size as a cue to distance; Radial motion. *American Journal of Psychology, 64,* 188-202. doi:10.2307/1418666

Judge, S. J. (1985). Can current models of accommodation and vergence control account for the discrepancies between AC/A measurements made by the fixation disparity and phoria methods? *Vision Research, 25,* 1999–2001. doi:10.1016/0042-6989(85)90026-4

Judge, S. J, & Miles, F. A. (1985). Changes in the coupling between accommodation and vergence eye movements induced in human subjects by altering the effective interocular separation. *Perception, 14,* 617–629. doi: 10.1068/p140617

Keller, E. L., & Robinson, D. A. (1972). Abducens unit behavior in the monkey during vergence eye movements. *Vision Research, 12,* 369–382. doi:10.1016/0042-6989(72)90082-X

Kenyon, R. V., Ciuffreda, K. J., & Stark, L. (1978). Binocular eye movements during accommodative vergence. *Vision Research, 18,* 545–555. doi:10.1016/0042-6989(78)90201-8

Kertesz, A. E. (1980). Human fusional vergence. *Proceedings of the eye movement conference, (OMS 80),* California Institute of Technology, Pasadena.

Kertesz, A. E, & Lee, H. J. (1987). Comparison of simultaneously obtained objective and subjective measurements of fixation disparity. *American Journal of Optometry & Physiological Optics, 64,* 734-738. doi:10.1097/00006324-198710000-00004

Khan, A. Z., & Crawford, J. D. (2001). Ocular dominance reverses as a function of horizontal gaze angle. *Vision Research, 41,* 1743-1748. doi:10.1016/S0042-6989(01)00079-7

Khokhotva, M., Ono, H., & Mapp, A. P. (2005). The cyclopean eye is relevant for predicting visual direction. *Vision Research, 45,* 2339–2345. doi:10.1016/j.visres.2005.04.007

LeConte, J. (1871). On some phenomena of binocular vision. *American Journal of Science, 1,* 33–44. doi:10.2475/ajs.s3-1.1.33

LeConte, J. (1881). *Sight: An exposition of the principles of monocular and binocular vision.* New York, NY: Appleton.

LeConte, J. (1897). *Sight: An exposition of the principles of monocular and binocular vision (2nd ed.).* New York, NY: Appleton.

Leibowitz, H. (1955). Effect of reference lines on the discrimination of movement. *Journal of the Optical Society of America, A2,* 829-830. doi:10.1364/JOSA.45.000829

Lejeune, A. (Ed.). (1956). *L'optique de Claude Ptolémée dans la version latine d'après l'arabe de l'Émir Eugène de Sicile.* Louvain: Université de Louvain.

Ludvigh, E., (1953). Direction sense of the eye. *American Journal of Ophthalmology, 36,* 139-142. doi:10.1016/0002-9394(53)90163-9

MacKay, D. M. (1958). Perceptual stability of a stroboscopically lit visual field containing self-luminous objects. *Nature, 181,* 507–508. doi:10.1038/181507a0

Mansfield, J. S., & Legge, G. E. (1996). The binocular computation of visual direction. *Vision Research, 36,* 27–41. doi:10.1016/0042-6989(95)00095-H

Mansfield, J. S., & Legge, G. E. (1997). Binocular visual direction, the cyclopean eye, and vergence: A response to Banks, van Ee and Backus (1997). Vision Research, 37, 1610–1613.

Mapp, A. P., & Ono, H. (1999). Wondering about the wandering cyclopean eye. *Vision Research, 39,* 2381-2386. doi:10.1016/S0042-6989(98)00278-8

Mapp, A. P., Ono, H., & Barbeito, R, (2003) What does the dominant eye dominate? A brief and somewhat contentious review. *Perception & Psychophysics, 65,* 310-317. doi:10.3758/BF03194802

Mapp, A. P., Ono, H., & Howard, I. P. (2002). Binocular visual direction. In I. P. Howard & B. J. Rogers, *Seeing in depth: Vol. 2. Depth perception* (pp. 85–99). Toronto: Porteous Publisher.

Mapp, A. P., Ono, H., & Howard, I. P. (2012). Binocular visual direction. In I. P. Howard & B. J. Rogers, *Perceiving in depth: Vol. 2. Stereoscopic vision.* (pp. 230–247). New York, NY: Oxford University Press.

Mapp, A. P., Ono, H., & Khokhotva, M. (2007). Hitting the target: Relatively easy, yet absolutely difficult? *Perception, 36,* 1139-1151. doi:10.1068/p5677

Mitson, L., Ono, H., & Barbeito, R. (1976). Three methods of measuring the location of the egocentre: Their reliability, comparative locations and intercorrelations. *Canadian Journal of Psychology, 30,* 1-8. doi:10.1037/h0082039

Moidell, B., Steinbach, M. J., & Ono, H. (1988). Egocenter localization in children enucleated at an early age. *Investigative Ophthalmology and Visual Science, 29 (8),* 1348–1351.

Ohtsuka, S. (1995a). Perception of direction in three–dimensional space with occlusion. *The Institute of Electronics, Information and Communication Engineers Tech Rep, 95,* 31-36. (Abstract in English).

Ohtsuka, S. (1995b). Relationship between error in inclination perception in observing Poggendorff figures and stereopsis. *The Institute of Electronics, Information and Communication Engineers Tech Rep, 95,* 24-26. (Abstract in English).

Ohtsuka, S., & Ono, H. (1998). Adjustment for displacement and compression triggered by pictorial cue of occlusion produces correct 3-D perception and Kanizsa's illusion. *Investigative Ophthalmology and Vision Science, 39,* S850.

Ohtsuka, S., & Yano, S. (1994). The phenomenon causing the Poggendorff illusion compensates geometrical error in reconstructed 2D image from stereopsis. *The Institute of Television Engineers of Japan (ITE) Tech Rep, 18-60,* 25-30. (Abstract in English).

Ohtsuka, S., Kawanura, H., & Kosugi, M. (1990). Two-dimensional image generation method based on binocular vision. Japanese Patent Application No. H2-122928 (in Japanese).

Ono, H. (1979). Axiomatic summary and deductions from Hering's principles of visual direction. *Perception & Psychophysics, 25,* 473-477. doi:10.3758/BF03213825

Ono, H. (1980). Hering's law of equal innervation and vergence eye movement. *American Journal of Optometry and Physiological Optics, 57,* 578–585. doi:10.1097/00006324-198009000-00008

Ono, H. (1981). On Wells's (1792) law of visual direction. *Perception & Psychophysics, 30,* 403–406. doi:10.3758/BF03206159

Ono, H. (1983). The combination of version and vergence. In C. M. Schor & K. J. Ciuffreda (Eds.), *Vergence eye movements: Basic and clinical aspects* (pp. 373–400). Toronto: Butterworth.

Ono, H. (1991). Binocular visual directions of an object when seen as single or double. In D. Regan (Ed.), *Vision and visual dysfunction: Vol. 9. Binocular vision* (pp. 1-18). New York, NY: MacMillan.

Ono, H., & Angus, R. G. (1974). Adaptation of sensory-motor conflict produced by the visual direction of the hand specified from the cyclopean eye. *Journal of Experimental Psychology, 103,* 1-9. doi:10.1037/h0036786

Ono, H., & Barbeito, R. (1982). The cyclopean eye vs. the sighting–dominant eye as the center of visual direction. *Perception & Psychophysics, 32,* 201–210. doi:10.3758/BF03206224

Ono, H., & Barbeito, R. (1985). Utrocular discrimination is not sufficient for utrocular identification. *Vision Research, 25,* 289-299. doi:10.1016/0042-6989(85)90121-X

Ono, H., & Gonda, G. (1978). Apparent movement, eye movement and phoria when two eyes alternate in viewing a stimulus. *Perception, 7,* 75-83. Also reprinted in Rock, I. (1997) (Ed.) Indirect Perception [Title changed to: Apparent motion based on changing phoria] (pp. 265-276). Cambridge: MIT Press.

Ono, H., & Lillakas, L. (1997). The visual system's solution to Leonardo da Vinci's paradox. *Proceedings of the fourth international display workshop, Nagoya, Japan, 4,* 831–834.

Ono, H., & Mapp, A. P. (1995). A restatement and modification of Wells–Hering's laws of visual direction. *Perception, 24,* 237–252. doi:10.1068/p240237

Ono, H., & Nakamizo, S. (1977). Saccadic eye movements during changes in fixation to stimuli at different distances. *Vision Research, 17,* 233-238. doi:10.1016/0042-6989(77)90087-6

Ono, H., & Nakamizo, S. (1978). Changing fixation in the transverse plane at eye level and Hering's law of equal innervation. *Vision Research, 18,* 511-519. doi:10.1016/0042-6989(78)90195-5

Ono, H., & Wade, N. J. (1985). Resolving discrepant results of the Wheatstone experiment. *Psychological Research, 47,* 135–142. doi:10.1007/BF00309264

Ono, H., & Weber, E. V. (1981). Nonveridical visual direction produced by monocular viewing. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 937-947. doi:10.1037/0096-1523.7.5.937

Ono, H., Angus, R., & Gregor, P. (1977). Binocular single vision achieved by fusion and suppression. *Perception & Psychophysics, 21,* 513–521. doi:10.3758/BF03198731

Ono, H., Lillakas, L., & Mapp, A. P. (2003). The making of the direction sensing system for the Howard eggmobile. In L. Harris & M. Jenkin (Eds.), *Levels of perception* (pp. 127–147). New York, NY: Springer Verlag. doi:10.1007/0-387-22673-7_7

Ono, H., Mapp, A. P., & Howard, I. P. (2002). The cyclopean eye in vision: the new and old data continue to hit you right between the eyes. *Vision Research, 42,* 1307–1324. doi:10.1016/S0042-6989(01)00281-4

Ono, H., Mapp, A. P., & Mizushina, H. (2007) The cyclopean illusion unleashed. *Vision Research, 47,* 2067-2075. doi:10.1016/j.visres.2007.03.001

Ono, H., Nakamizo, S., & Steinbach, M. J. (1978). Non-additivity of vergence and saccadic eye movement. *Vision Research, 18,* 735-739. doi:10.1016/0042-6989(78)90152-9

Ono, H., Ohtsuka, S., & Lillakas, L. (1998). The visual system's solution to Leonardo da Vinci's paradox and to the problems created by the solution. *Proceeding for The Workshop on Visual Cognition,* 125-136.

Ono, H., Shimono, K., Saida, S., & Ujike, H. (2000). Transformation of visual line in binocular vision: Stimuli on corresponding points can be seen in two different directions. *Perception, 29,* 421-436. doi:10.1068/p2906

Ono, H., Tam, W. J., & McConnell, S. (1983). Apparent displacement with a monocular prism differs from optical displacement. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 652-656. doi:10.1037/0096-1523.9.4.652

Ono, H., Wade, N. J., & Lillakas, L. (2002). The pursuit of Leonardo's constraint. *Perception, 31,* 83-102. doi:10.1068/p3079

Ono, H., Wade, N. J., & Lillakas, L. (2009). Binocular vision: Defining the historical direction. *Perception 38,* 492-507. doi:10.1068/p6130

Ono, H., Wilkinson, A., Muter, P., & Mitson, L. (1972). Apparent movement and change in perceived location of a stimulus produced by a change in accommodative vergence. *Perception & Psychophysics, 12,* 187-192. doi:10.3758/BF03212868

Owens, D. A., & Leibowitz, H. W. (1975). The fixation point as a stimulus for accommodation. *Vision Research, 15,* 1161–1163. doi:10.1016/0042-6989(75)90016-4

Owens, D. A., & Tyrrell, R. A. (1992). Lateral phoria of distance: contributions of accommodation. *Investigative Ophthalmology and Vision Science, 33,* 2733-2743.

Park, K., & Shebilske, W. L. (1991). Phoria, Hering's law and monocular perception of direction. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 219 - 231. doi:10.1037/0096-1523.17.1.219

Parson, B. S. (1924). *Lefthandedness.* New York, NY: MacMillan.

Pelz, J. B., & Hayhoe, M. M. (1995). The role of exocentric reference frames in the perception of visual direction. *Vision Research, 35,* 2267–2275. doi:10.1016/0042-6989(94)00314-C

Popple, A. V., & Findlay, J. M. (1998). Is monocular alignment computed by binocular neurons? *Investigative Ophthalmology and Vision Science, 39,* S622.

Porac, C., & Coren, S. (1981). *Lateral preferences and human behavior.* New York, NY: Springer–Verlag. doi:10.1007/978-1-4613-8139-6

Porterfield, W. (1737). An essay concerning the motions of our eyes. Part 1. Of their external motions. *Edinburgh Medical Essays and Observations, 3,* 160-263.

Regan, D., & Beverley, K. I. (1978). Looming detectors in the human visual pathway. *Vision Research, 18,* 415-421. doi:10.1016/0042-6989(78)90051-2

Regan, D., Erkelens, C. J., & Collewijn, H. (1986). Necessary conditions for the perception of motion in depth. *Investigative Ophthalmology and Vision Science, 27,* 584–597.

Remole, A. (1983). Border enhancement as a function of binocular fixation performance. *American Journal of Optometry & Physiological Optics, 60,* 567–577. doi:10.1097/00006324-198307000-00003

Remole, A. (1984). Binocular fixation misalignment measured by border enhancement: A simplified technique. *American Journal of Optometry & Physiological Optics, 61,* 118–124. doi:10.1097/00006324-198402000-00009

Remole, A. (1985). Fixation disparity vs. binocular fixation misalignment. *American Journal of Optometry & Physiological Optics, 62,* 25–34. doi:10.1097/00006324-198501000-00003

Riggs, L. A., & Niehl, E. W. (1960). Eye movements recorded during convergence and divergence. *Journal of the Optical Society of America, 50,* 913-920. doi:10.1364/JOSA.50.000913

Ripps, H., Chin, N. B., Siegel, I. M., & Breinin, G. M. (1962). The effect of pupil size on accommodation, convergence, and the AC/A ratio. *Investigative Ophthalmology & Visual Science, 1,* 127–135.

Roelofs, C. O. (1959). Considerations on the visual egocentre. *Acta Pscyologica, 16,* 226–234. doi:10.1016/0001-6918(59)90096-4

Rubin, M. L., & Walls, G. L. (1969). *Fundamentals of visual science.* Springfield, IL: Charles C. Thomas.

Saida, S., Ono, H., & Mapp, A. P. (2001). Closed-loop and open-loop accommodative vergence eye movements. *Vision Research, 41,* 77–86. doi:10.1016/S0042-6989(00)00233-9

Schroeder, T. L., Rainey, B. B., Goss, D. A., & Grosvenor, T. P. (1996). Reliability of and comparisons among methods of measuring dissociated phoria. *Optometry and Vision Science, 73,* 389–397. doi: 10.1097/00006324-199606000-00006

Sheard, C. (1926). Unilateral sighting and ocular dominance. *American Journal of Physiological Optics, 7,* 558–567.

Sheedy, J. E., & Fry, G. A. (1979). The perceived direction of the binocular image. *Vision Research, 19,* 201–211. doi:10.1016/0042-6989(79)90051-8

Shimono, K., & Tam, W. J. (2002). Apparent motion and distortion of monocular stimuli through depth capture. *Proceedings of the Second Asian Conference on Vision,* 3.

Shimono, K., Ono, H., Saida, S., & Mapp, A. P. (1998). Methodological caveats for monitoring binocular eye position with Nonius stimuli. *Vision Research, 38,* 591–600. doi:10.1016/S0042-6989(97)00168-5

Shimono, K., Tam, W. J., & Ono, H. (2007). Apparent motion of monocular stimuli in different depth planes with lateral head movements. *Vision Research, 47,* 1027-1035. doi:10.1016/j.visres.2007.01.012

Shimono, K., Tam, W. J., Asakura, N., & Ohmi, M. (2005). Localization of monocular stimuli in different depth planes. *Vision Research, 45,* 2631–2641. doi:10.1016/j.visres.2005.05.003

Smith, A. M. (1996). *Ptolemy's theory of visual perception: An English translation of the Optics with introduction and commentary.* Philadelphia, PA: The American Philosophical Society.

Snowden, R. J. (1992). Sensitivity to relative and absolute motion. *Perception, 21,* 563-568. doi:10.1068/p210563

Steinbach, M. J., Howard, I. P., & Ono, H. (1985). Monocular asymmetries in vision: we don’t see eye to eye. Canadian Journal of Psychology, 39, 476–478. doi:10.1037/h0080075

Sterken, Y., Postma, A., de Haan, E. H. F., & Dingemans, A. (1999). Egocentric and exocentric spatial judgements of visual displacement. *The Quarterly Journal of Experimental Psychology, 52A (4),* 1047-1055. doi:10.1080/713755862

Stevens, S. S. (1935). The operational definition of psychological concepts. *Psychological Review, 42,* 517-527. doi:10.1037/h0056973

Swindle, P. F. (1916). Positive after-images of long duration. *American Journal of Psychology, 27,* 324-334. doi:10.2307/1413101

Teuber, H. L. (1960). Perception. In J. Field, H. W. Magoun, & V.E. Hall (Eds.), *Handbook of physiology: Neurophysiology* (pp. 1595-1668). Washington, DC: American Psychological Society.

Towne, J. (1865). The stereoscope, and stereoscopic results – Section VI. *Guy's Hospital Reports, 11,* 144–180.

Towne, J. (1866). Contributions to the physiology of binocular vision – Section VII. *Guy's Hospital Reports, 12,* 285-301.

Towne, J. (1869). Contributions to the physiology of binocular vision – Section VIII. *Guy's Hospital Reports, 14,* 54–83.

Towne, J. (1870). Contributions to the physiology of binocular vision – Section IX. *Guy's Hospital Reports, 15,* 180–212.

Tyler, C. W. (1997). On Ptolemy's geometry of binocular vision. *Perception, 26,* 1579-1581. doi:10.1068/p261579

van de Grind, W. A., Erkelens, C. J., & Laan, A. C. (1995). Binocular correspondence and visual direction. *Perception, 27,* 215-235. doi:10.1068/p240215

Wade, N. J. (2003). *Destined for distinguished oblivion: The scientific vision of William Charles Wells (1757–1917).* New York, NY: Kluwer/Plenum. doi:10.1007/978-1-4615-0213-5

Wade, N. J., & Swanston, M. T. (1987). The representation of nonuniform motion: induced motion. *Perception, 16,* 555-571. doi:10.1068/p160555

Wade, N. J., Ono, H., Mapp. A. P. (2006). The Lost Direction in Binocular Vision: The Neglected Signs Posted by Wells, Towne, and LeConte. *Journal of the History of the Behavioral Sciences, 42,* 61–86. doi:10.1002/jhbs.20135

Walls, G. L. (1951). A theory of ocular dominance. *A.M.A. Archives of Ophthalmology, 45,* 387–412. doi:10.1001/archopht.1951.01700010395005

Welch, R. B. (1986). Adaptation of space perception. In K. R. Boff, L. Kaufman & J. P. Thomas (Eds*.). Handbook of perception and human performance: Volume 1 Sensory processes and perception* (chap. 24). New York, NY: Wiley.

Wells, W. C. (1792). *An essay upon single vision with two eyes: Together with experiments and observations on several other subjects in optics.* London: Cadell.

Westheimer, G., & McKee, S. P. (1977). Spatial configurations for visual hyperacuity. *Vision Research, 17,* 941-947. doi:10.1016/0042-6989(77)90069-4

Westheimer, G., & Mitchell, A. M. (1956). Eye movements responses to convergence stimuli. *Archives of Ophthalmology, 55,* 848-856. doi:10.1001/archopht.1956.00930030852012

Yarbus, A. L. (1967). Eye movements and vision. L. A. Riggs (Ed.). (B. Haigh, Trans.). New York, NY: Plenum Press. (Original work published 1965) doi:10.1007/978-1-4899-5379-7

Zenkin, G, M., & Petrov, A. P. (1979). On the constancy mechanisms for visual space perception. *Sensory Systems [SENSORNYE SISTEMY],* Nauka, Leningrad, 25-39. (This is a publication, which came out every year in Pavlov Institute of Physiology in Leningrad. Thanks to Dr. Nikolaev [Institute for Information Transmission Problems, Russian Academy of Sciences] for tracking down the paper and Dr. L. Kontsevich [Smith-Kettlewell Eye Research Institute] for translating the critical part of the paper into English.)