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Binocular vision: Defining the historical directions

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Abstract. Ever since Kepler described the image-forming properties of the eye (400 years ago) there has been a widespread belief, which remains to this day, that an object seen with one eye is always seen where it is. Predictions made by Ptolemy in the first century, Alhazen in the eleventh, and Wells in the eighteenth, and supported by Towne, Hering, and LeConte in the nineteenth century, however, are contrary to this claimed veridicality. We discuss how among eighteenth- and nineteenth-century British researchers, particularly Porterfield, Brewster, and Wheatstone, the erroneous idea continued and also why observations made by Wells were neither understood nor appreciated. Finally, we discuss recent data, obtained with a new method, that further support Wells's predictions and which show that a distinction between headcentric and relative direction tasks is needed to appreciate the predictions.

1 Introduction

The history of research on vision reflects a struggle between two approaches, the origins of which can be traced to antiquity. Both are based initially on the observation of objects, but differing emphasis is placed on the observations themselves. One is concerned principally with phenomenology and has relatively little in the way of theory derived from the observations. The other relates the basic phenomena to an underlying theory (optics or geometry) after which the observations become subservient to that theory. The former is concerned with visual directions as they are observed and the latter with the lines of light from objects to the eyes.

The observational tradition was espoused by Aristotle, but its ablest early protagonist in binocular vision was Ptolemy (c. 150) in the second century AD (see Howard and Wade 1996; A M Smith 1996; Tyler 1997). The optical tradition was most clearly enunciated by Euclid (c. 300 BC) when he reduced space perception to the geometry of light rays—from a focus at the eye to objects in space. Euclid examined binocular vision in the context of lines from each eye to spheres differing in diameter with respect to the interocular separation. While Euclid's analysis of binocular vision was geometrical, it was also cursory; he examined three dimensions of spheres that could be observed by two eyes, and simply related them to the amount of the spheres encompassed by the lines of light from the two eyes. In contrast, Ptolemy was thorough; he carried out controlled observations of the perceived locations of vertical cylinders. From these he specified the conditions for singleness of vision and distinguished between the crossed and uncrossed directions in which objects are seen with two eyes. In the eleventh century, Alhazen (or Ibn al-Haytham) extended Ptolemy's analysis (see Howard 1996; A M Smith 2001).

Ptolemy constructed a board on which he placed vertical rods at different distances in the midline between the eyes (see figure 1). He provided a description of one of the most commonly used examples of crossed and uncrossed visual directions: with fixation on a distant rod in the midline of the head, a nearer one appeared double (to the left with the right eye and to the right with the left eye); the reverse occurred with

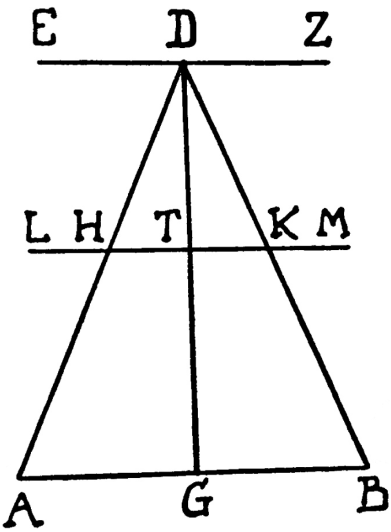

Figure 1. Ptolemy's board for examining visual direction in monocular and binocular vision. He wrote "when the line *htk* is produced parallel to *edz*, and the eyes are converged on point *d*, an object at point *t* will be seen in two locations *h* and *k*". (Figure and translation from Lejeune 1956, pages 102 – 103.)

fixation on a nearer rod. These observations were interpreted in terms of the visual axes and the common axis. Similar experiments were conducted by Alhazen (see Sabra 1989; A M Smith 2001) and Wells (1792), who formulated the principles of visual direction in binocular vision. Wells's principles were rediscovered in the nineteenth century by Towne (1866), Hering (1868/1977, 1879/1942), and LeConte (1871) (see Ono 1981; Wade et al 2006).

The optical tradition was based upon lines drawn from the eye to objects until the dioptrical properties of the eye were described by Kepler, in the early seventeenth century (Wade 2007a). Thereafter, lines of light were drawn to, rather than from, the eye and representing the characteristics of retinal images became commonplace. However, analyses of binocular vision remained confined to singleness with corresponding stimulation, and double vision when not in correspondence. This situation was transformed by Wheatstone (1838), who essentially conflated the observational and optical perspectives. By means of the stereoscope, Wheatstone was able to present defined horizontal differences in the pictures to each eye to yield predictable relative depth perception. Despite this, he maintained Kepler's idea of projection to each eye.

The aims of this paper are fivefold. First was to show that the optical analysis was accepted as a matter of course in the seventeenth- to nineteenth-century English literature on vision and that there was a general consensus that objects seen with one eye are correctly localised. Second was to indicate that this idea was extended to binocular vision. Third was to argue that this consensus is contrary to predictions made by Ptolemy, Alhazen, and Wells (1792), followed by those of Towne (1866), Hering (1868/1977, 1879/1942), and LeConte (1871, 1881). In order to clarify the contradiction, we illustrate the predictions from Wells's propositions. (Predictions from Towne, Hering, and LeConte's writings on visual direction are also illustrated, because they add credence to Wells's predictions.) Fourth was to discuss results of a recent study with a new methodology, which show that support for the predictions depends on the task performed. Fifth was to speculate on why the consensus lasted for such a long period and still permeates the contemporary literature.

2 Historical accounts of visual direction

Kepler (1604, 1611) launched the modern era in vision research; he provided an analysis of the first stages of vision in terms of projections to the retina and he interpreted monocular visual direction in projective terms:

> "I say that vision occurs when an image of the whole hemisphere of the world that is before the eye, and a little more, is set up at the white wall, tinged with red, of the concave surface of the retina. How this image or picture is joined together with the visual spirits that reside in the retina and in the nerve, and whether it is arraigned within by the spirits into the caverns of the cerebrum to the tribunal of the soul or of the visual faculty; whether the visual faculty, like a magistrate given by the soul, descending from the headquarters of the cerebrum outside to the visual nerve itself and the retina, as to lower courts, might go forth to meet this image—this, I say, I leave to the natural philosophers to argue about." (Kepler 1604, translated in Donahue 2000, page 180)

That is, Kepler made an explicit distinction between the physical optics of image formation and the psychological optics of vision, but he did not have much to say about the latter. He also grappled with the problems of visual experience being projected beyond the eyes and of visual direction, although his speculations were based more on optics than on observation:

> "The position of an object is estimated from the direction in which the ray of sight *originally* emerges from the eye, no matter how this direction may be altered by refraction in its path between the eye and the object. For the eye *cannot detect* what happens to the rays outside itself in intervening media, but *assumes* that these proceed in the original direction." (Mach 1921, translated by Anderson and Young 1926, page 44, original italics)

2.1 *English researchers after Kepler on Porterfield's axiom or Brewster's law of visible direction*

Kepler's idea was elevated to an axiom or a law of visible direction by some later writers, although Kepler's name was not always associated with it. Similar statements regarding visual direction of a monocular stimulus can be found in Porterfield (1737), R Smith (1738), Reid (1764), Young (1801), and Brewster (1830).

Among these writers, Porterfield (1737) made the most explicit and succinct statement, and he was so confident in its validity that he called it an axiom. He stated: "*Every Point of an Object appears and is seen without the Eye nearly in a straight Line, drawn perpendicularly to the Retina, from that Point of it where its Image falls*" (page 208, original italics).[(1)] R Smith (1738) thought the principal ray of light rather than the retinal locus was responsible for visible direction but the idea of projection was maintained. He wrote, "Any small object or part of an object, seen by refracted or reflected rays, appears somewhere in the direction of that line, which the visual ray describes after its last refraction or reflection in falling upon the eye" (R Smith 1738, page 32). Reid and Young, however, sided with Porterfield: "... every point of the object is seen in the direction of a right line passing from the picture of that point on the retina through the centre of the eye" (Reid 1764, page 289) and "In the eye, we judge very precisely of the direction of light, from the part of the retina on which it impinges" (Young 1801, pages 25–26).

Brewster (1830) was more elaborate and just as confident as Porterfield about the validity of his assertion that he labeled it a 'law'. He linked the projective definition of visual (or 'visible' in his terms) direction to retinal anatomy so that: "we know nothing more than that the mind, residing, as it were, in every point of the retina, refers the impression made upon it at each point to a direction coinciding with the last portion of the ray which conveys the impression" (page 615). Brewster (1844a), not mentioning Porterfield in this context, made a strong claim for the validity of Porterfield's axiom,

[(1)] Strictly speaking, the visual line that passes through the image formed on the periphery of the retina would not be perpendicular to the retina. This is so because the nodal point of the eye is in front of the centre of rotation of the eye (Emsley 1977; Gulick and Lawson 1976). The nodal point being in front causes the ocular parallax described by Brewster (1844a). See Mapp and Ono (1986) for an illustration of ocular parallax.

even though he found that stimulation of the peripheral retina gave rise to "visible objects different from their real position" (page 351). He coined the term ocular parallax for the difference and argued that it occurs only in peripheral vision and that the deviation of visible direction from the line of real direction is "very minute" (page 352). With the following experiment, Brewster felt that he had established that the law of visible direction was "substantially true" (page 352):

> "That a visible point is seen in the direction of a line perpendicular to the surface of the retina at which the image of the point is formed, may be established experimentally in the following manner. Having expanded the pupil by belladonna, look directly at a point in the axis of the eye. Its image will be formed by a cone of rays variously inclined from 85° to 90° to the surface of the retina. While the point is distinctly seen, intercept all these different rays in succession, and it will be found that each ray gives vision in the same direction, the visible point retaining its position. Hence it follows, that on the part of the retina in the axis of vision, all rays, however obliquely incident, give the same visible direction perpendicular to the surface of the membrane. That the same property is possessed by every other part of the retina cannot be doubted, and may be proved by direct experiment." (Brewster 1844a, page 352)

2.2 *Extension of the axiom or the law to binocular direction and its restatement*

Brewster further argued that the law of visible direction applied to binocular vision. He agreed with Wheatstone (1838) "that the results of any attempt to explain the single appearance of objects to both eyes, or, in other words, *the law of visible direction for binocular vision*, ought to contain nothing inconsistent with the law of visible direction for monocular vision" (Wheatstone 1838, page 388, quoted by Brewster who added the italics). Brewster (1844a) continued: "Properly speaking, however, there is no such thing as a law of visible direction in binocular vision, because there is no such thing as *a centre* of visible direction, or *a line* of visible direction in binocular vision" (page 354, original italics). This latter statement contrasts with the concept of the central eye, the double eye, or the cyclopean eye as proposed by Towne (1866), Hering (1868/1977), and LeConte (1871, 1881),(2) respectively, only twenty-some years after Brewster's writing. [Having proposed a reference point for visual direction between the two eyes, these three authors made identical predictions regarding visual direction (Wade et al 2006).]

Before we proceed further, we summarise the projective hypothesis that Kepler (1604, 1611) initiated and that was advocated by a long list of writers. The hypothesis was worded in many different ways but can be stated succinctly with modern terminology; it is that *objects seen with either eye are seen on their respective visual lines*. The 'visual line' is defined as "any straight line passing through [an object], the pupil and the nodal point of an eye" (Howard and Rogers 2002, page 86). In our view, the term 'visual line' is unfortunate because it denotes the physical line and not the perceptual as in 'visual direction' or 'visual distance'. The term would be appropriate if Porterfield's (1737) axiom or Brewster's (1844a) law of visible direction were valid, but it is not as we show below. Henceforth, the axiom and the law are referred to as Porterfield's axiom, since we analyse Porterfield binocular stimuli to contrast his prediction based on projection or geometry to that of Wells.

2.3 *Contrasting Wells's predictions with those from Porterfield's axiom*

Not all students of vision in the eighteenth century adopted the optic or projective theory of visual direction. One notable exception was Wells (1792), who conducted experiments on visual direction with two eyes and reported these in his monograph *An Essay upon Single Vision with Two Eyes*. While not aware of Ptolemy's enquiries, Wells acknowledged that he was addressing an issue that had demanded consideration

(2) Hering (1879/1942, page 43) also used the term "cyclopean eye" later on.

by some of the greatest minds of the past. The authorities he cited were anatomists, like Galen, Briggs, and Porterfield; students of optics, like Alhazen, Aguilonius, Newton, and Smith; and philosophers, like Berkeley and Reid. Ptolemy's *Optics* was not available to Wells; Latin versions of it were not rediscovered until the late-eighteenth and early-nineteenth centuries (see A M Smith 1996). A Latin version of Alhazen's book was printed in 1572, but most reviews of the books were concerned with optics and not with perception (Howard 1996), and therefore it may be that Wells was unaware of Alhazen's work on perception as well as that of Ptolemy.

Wells (1792) proceeded to present his own analysis of single vision and advanced a novel theory to account for it. He was assiduous in defining the terms that he employed. For example, the optic axis (today called the visual axis) was determined by means of a visual-alignment task—when a small, fixated target can be obscured by a closer small object then the optic axis is the line joining them and the eye. The visual base was essentially the interocular separation, and the common axis was a line from the middle of the visual base to the point where the optic axes intersect. These were described by Wells in his text, but he did not provide any figures to illustrate them; they are shown diagrammatically in Ono (1981) and Wade (2003). One of the experiments he conducted was to view an object through two small holes, one in front of each eye. The object was perceived to lie on the common axis; this point was not novel and was not contested. However, unlike earlier commentators, Wells considered the perception of the holes as well as the object: the holes appeared single and on the common axis as well. When the holes were moved further from the eyes and made closer to each other, they were still perceived as a single hole on the common axis. The novelty of Wells's theory was his demonstration that visual direction was not determined by retinal values alone, but involved the action of the muscles controlling eye position. Unfortunately, his theory had virtually no impact on vision research during his lifetime or after, because the prevailing interpretation of binocular vision was in terms of retinal correspondence.

To examine the validity of Porterfield's axiom and to contrast it with Wells's observation, we go back to Porterfield's (1737, 1738) writing. His statement regarding visual direction and his illustration of three binocular stimulus situations to which he applied his axiom serve this purpose well because of their explicitness. The three stimulus situations are shown in figure 2. It is noteworthy that Porterfield's figure 5 anticipated Panum's limiting case (see Wade 2007b). About these figures Porterfield wrote:

> "..., *see Fig. 3, 4, and 5*, where A and B are the Eyes, *x* the Object, which is at a smaller Distance than the Point C, to which both Eyes are directed, it is evident, that while the eyes continue directed to C, the Object *x* must be seen in two different Places, which, with respect to the *Horopter*, to which all Objects are referred, will be D and E; for being seen by the right Eye B, in the Direction of the visual Line B*x*D, it must, at D, hide a Part of the *Horopter* DCE; and being seen by the left Eye A, in the Direction of the visual Line A*x*E, it must hide a Part of the *Horopter* at E, and therefore, with respect to the *Horopter* on which the Eyes are fixed at C, the Object *x* must appear to the right Eye B, as at D, and to the Left Eye A as at E; and in covering either of the Eyes, the Appearance that is on the contrary Side will be made to vanish. In like manner, if the Eyes are directed to *x*, the Object C, which is further off the *x*, will be seen by the Right Eye B, in the Direction of the visual Line B*m*C; and by the Left Eye A, it will be seen in the Direction of the visual Line A*o*C; and therefore, with respect to the *Horopter mxo*, to which all Objects are referred, it must appear double, as at *m* and *o*; and in covering the Right Eye B, the Appearance that is on the Right Side towards *m* will vanish; and in covering the Left Eye A, the Appearance that is on the Left Side towards *o* will vanish; all which is exactly agreeable to Experience." (1738, pages 156–158, original italics)

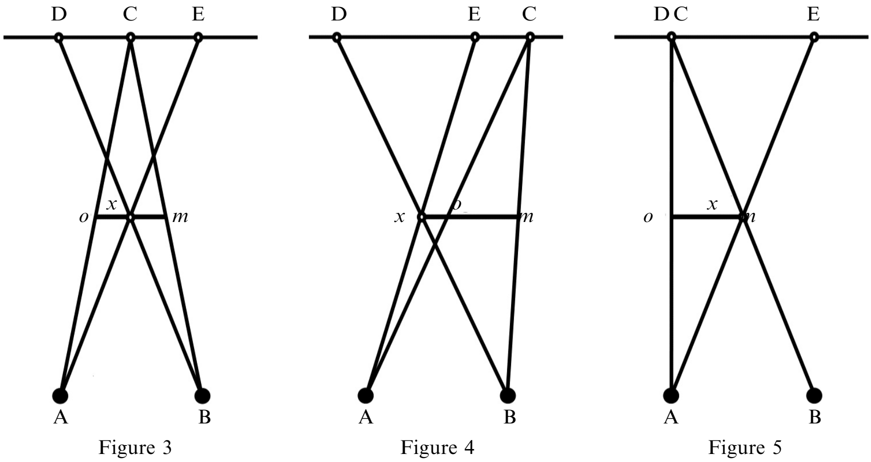

Figure 2. Binocular stimuli discussed by Porterfield (1738). His figures 3, 4, and 5 are redrawn.

Although Porterfield's (1738) observation as to which diplopic image disappears when one eye is closed is correct, the apparent locations of the diplopic images are not predicted correctly by his axiom if the visual distances of the diplopic images coincide with the actual distances. More specifically, the predictions from his axiom differ from Wells's (and Towne/Hering/LeConte's) predictions. Here we compare Porterfield's figure 3 as analysed by him, and Wells's (and Towne/Hering/LeConte's) predictions. (For analyses of his two other stimulus situations, his figures 4 and 5 in our figure 2, see the Appendix.)

Note that in Porterfield's (1738) illustration (his figure 3) that Objects C or *x*, respectively, whether C or *x* is fixated, are located on the common axis (the line passing through the intersection of the two visual axes and the midpoint of "the interval between the points of the cornea where the [visual] axes enter the eyes" (Wells 1792, page 38). We consider Wells's prediction first in the second row of figure 3. Wells's Proposition II explicitly deals with this stimulus situation and states: "Objects, situated in the Common Axis, do not appear to be in that Line, but in the Axis of the Eye, by which they are not seen" (1792, page 46). For Towne/Hering/LeConte's predictions, see the third row of figure 3. Also, note that Ptolemy made the same prediction as both Wells and Towne/Hering/LeConte (see figure 1): while fixation is on D, T is seen at H and K. All three predictions are illustrated with an assumption that the diplopic images are seen in their correct distances. Under this assumption, these predictions clearly violate Porterfield's (1737) axiom that states "*Every Point of an Object appears ... in a straight Line, drawn perpendicularly to the Retina, from that Point of it where its Image falls*" (page 208, original italics). However, our statement regarding the violation needs a qualification; Porterfield (1738) wrote "... while the eyes continue directed to C, the Object *x* must be seen in two different Places, which, with respect to the *Horopter*, to which all Objects are referred ..." (1738, page 156, original italics). The meaning of 'all Objects are referred to the Horopter' is not clear to us, but if it means that diplopic images are seen on the horopter, his prediction agrees with that of Towne/Hering/LeConte, but not with that of Wells.(3) For the example given in figure 3, the common

(3) One reviewer of this paper wrote, "Based on Gogel's adjacency principle (eg Gogel 1972), one might expect off-horopteral targets (especially monocular ones) to be perceived close to the distance of the binocular fixation stimulus if the lateral separation is small, and farther from the fixation plane if the lateral separation is large". We do not know of any experiments that address this issue, but in the experiment to be described shortly a fixation stimulus (LED) was presented at 30 cm and a monocular stimulus (another LED) at 10 cm, and they were never reported as being perceived at equal distances.

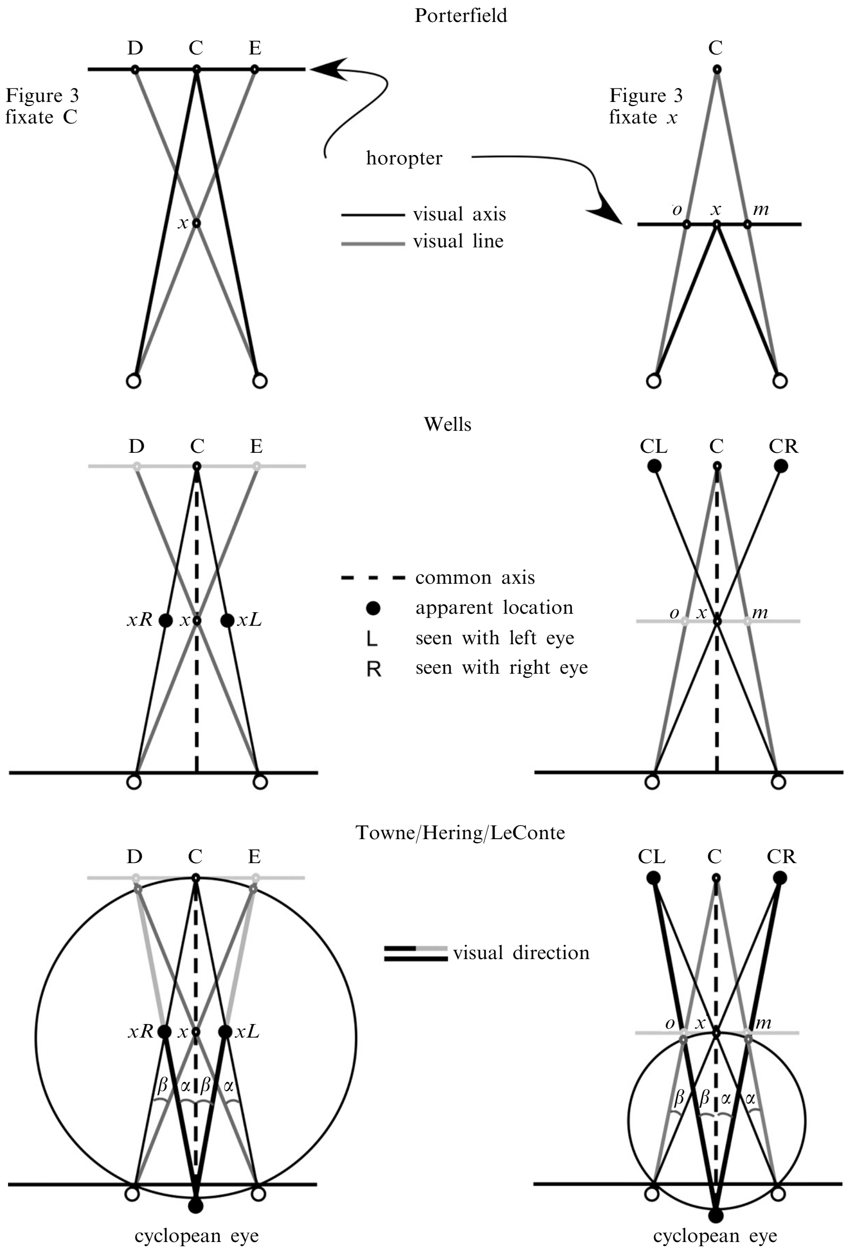

Figure 3. Predictions for Porterfield's figure 3 by Porterfield, Wells, and Towne/Hering/LeConte. See text for Wells's prediction. Hering's prediction is based on the idea that the visual angle subtended by *x* and C is transferred to the cyclopean eye and the visual axis transferred to the common axis (Ono and Mapp 1995). In this figure, figure A1, and figure A2, Porterfield's labels, from the first panel, are used in the other two panels and the legends in each panel apply to all panels.

axis and the two visual axes converged to a point on the horopter, and *x* would appear superimposed onto C, which Wells argued would not happen. See the Appendix for Wells's argument.

Given this argument against Porterfield's axiom, the question arises how did Wheatstone (1838) and Brewster (1844a, 1844b) react to Wells's writing? It appears that the assumptions about visible direction, which had prevailed for over 200 years at that time, were so strong that Wells's propositions could not be understood. Wheatstone dismissed Wells's writings as:

> "Dr. Wells's 'new theory of visible direction' was a modification of the preceding hypothesis [cf Aguilonius 1613]. This acute writer held with Aguilonius, that objects are seen single only when they are either before or beyond it, but he attempted to make this single appearance of objects only in the plane of the horopter to depend on other principles, from which deduced ... So little does Dr. Wells theory appear to have been understood, that no subsequent writer has attempted either to conform or disprove his opinions. It would be useless here to discuss the principles of this theory, which was framed to account for the anomalous individual fact since it is inconsistent with the general rules on which that has been now shown to depend. Notwithstanding these erroneous views, the 'essay upon single vision with two eyes' contains many valuable experiments and remarks, the truth of which are independent of the theory they were intended to illustrate." (Wheatstone 1838, page 388)

Wheatstone (1838) was justifiably reacting to Wells's (1792) propositions predicting incorrectly that any object not on the horopter would be seen double. However, he missed the fact that the propositions predict correctly the apparent locations of diplopic images and that of a stimulus occluded from one eye (for the latter, see figure A2 in the Appendix). It is a puzzle to us why Wheatstone missed this point, since Wells provided ample evidence to justify the propositions. If Wheatstone had not missed it, he would have realised that Wells's propositions were not "erroneous" for predicting the apparent locations of diplopic images and were not "framed to account for the anomalous individual fact" (quotes from the previous paragraph). The prestige of Wheatstone was such that the quote above is one of the factors that contributed to Wells's being "destined for distinguished oblivion" (the title of Wade's book on Wells) and his ideas being neglected in the history of visual science (Wade 2003; Wade et al 2006).

Brewster (1844b) was kinder to Wells. After describing several illusions, he acknowledged "the late Dr. Wells" (page 670) and explained the illusions using Wells's Proposition I that states, "Objects situated in the Optic Axis, do not appear to be in that Line, but in the Common Axis" (Wells 1792, page 40). It appears that Brewster did not recognise that this proposition contradicted the law of visible direction that he so strongly advocated. He described one of Wells's experiments that justified his explanation thus: "... if we hold two thin rules in such a manner that their sharp edges shall be in the optics axes, one of each, or rather a little below them, *the two edges will be seen united in the common axis*" (Wells 1792, page 44, quoted by Brewster who added the italics). This experimental result, as described by Wells, clearly contradicts the view that had prevailed for over 200 years at that time and still persists today.

Perhaps, some of the blame for Wells not being understood falls on Wells himself. If he had explicitly pointed out, as we have, that the predictions from the propositions do not agree with Porterfield's axiom, Wheatstone (1838) and Brewster (1844a) may have made more of an effort to examine Wells's propositions. With greater effort, they may have realised that the axiom they subscribed to makes different predictions.

2.4 *Recent confirmation of Wells's predictions*

Whatever the reason for Wells not explicitly challenging Porterfield's axiom, how can we explain the lack of recognition given to Wells and the long survival of the axiom? As far as we know, no one has challenged the axiom, although there are recent challenges to the concept of the cyclopean eye (Erkelens 2000; Erkelens and van Ee 2002). To discuss this lack of challenge and the long survival of the idea that underlies the axiom, we first describe a recent study by Khokhotva et al (2005), which was conducted in a dispute regarding the cyclopean eye but the results of which are useful to the present discussion.

Khokhotva et al (2005) had a fixation point in the median plane (at 30 cm) and flashed one of thirteen monocular stimuli closer to the face (at 10 cm) in a given trial. Two of the thirteen stimuli were collinear with respect to one of the eyes and the fixation stimulus, and one of them was collinear with respect to the bridge of nose. The fixation stimulus was seen binocularly in one third of the trials and monocularly in two thirds of the trials. In half of the monocular conditions, the fixation and target stimuli were seen with the same eye, whereas in the other half they were seen with different eyes. Pertinent for the purpose of this paper is that there were two different tasks on each trial.

One was a headcentric (referred to as egocentric by Wade and Swanston 2001) task,[(4)] in which the observer was asked to judge where an imaginary line passing through the two points appears to point—on or beside his or her face. The imaginary line always pointed to the face or beside it—incorrectly as predicted by Wells's propositions. The line passing through the fixation point and an eye appeared to point to the nose, and the line passing through the fixation point and the nose appeared to point to an eye as shown in the middle section of figure 3.

The second task was a relative direction task, in which an observer was asked whether the closer stimulus appeared to the left of, to the right of, or in the same direction as the fixation stimulus. The relative direction judgments were correct in over 99% of the trials when we exclude the stimulus condition in which the two stimuli were aligned to one eye or the two conditions in which the two stimuli were closest to being aligned. The correct responses were defined as those predicted by Wells's propositions or defined objectively with respect to the eye which viewed the stimuli. For a relative-judgment task, these two definitions would make the same prediction in the binocular condition. The predictions became complicated, however, because the head was not stabilised with a bite board and a slight head movement broke the alignment of the two stimuli and the eye, which observers were sometimes able to detect as two stimuli not pointing exactly to the nose. Moreover, in the monocular-fixation conditions the occluded eye would deviate the line passing through the fixation stimulus and the nodal point. The deviation (phoria) would move the common axis and changed the prediction in the monocular condition from that of the binocular condition. For simplicity we have used the prediction in the binocular condition to define the correct relative judgment. The relative direction judgments were correct in 82% of the excluded trials. For details and for an illustration of the predicted effect of phoria, see Khokhotva et al (2005).

The results from this study bear upon the matters at hand in several ways. First, the data derived from the headcentric task confirmed Wells's (and Towne/Hering/LeConte's) predictions but not those based on Porterfield's axiom. The monocular near stimuli were seen in incorrect locations and did not appear on their visual lines. To understand Wells's (Ptolemy's or Towne/Hering/LeConte's) predictions without referring to the propositions, consider an object in front of or behind a fixation plane that appears double. But diplopic images are seen in incorrect directions on both sides of the object's actual location. When viewed monocularly, it is seen in one of those two incorrect locations depending on which eye is occluded (or viewing). The apparent location of either image does not fall on the visual line of the object unless the images

[(4)] Khokhotva et al (2005), Mapp et al (2007), Ono and Mapp (1995), and Ono et al (2003) used the term 'absolute direction' for what we call 'headcentric direction'. The term 'absolute' contrasts better with the term 'relative', and the term 'absolute direction' is analogous to the term 'absolute distance' in the literature. We, however, avoided the term 'absolute' in this paper, because the direction we refer to is relative to an observer. We also avoided the term 'egocentric direction' as used by Wade and Swanston (2001), because 'torsocentric direction' (also egocentric) can be quite different from headcentric direction, depending on head position.

are perceived to be in the fixation plane. By definition, the visual line passes through the object.

Second, to falsify or to support either hypothesis (Wells's or Porterfield's), the task and stimuli must be carefully chosen. (a) In addition to Khokhotva et al's (2005) method, another possible headcentric task for testing the hypotheses would be pointing to the apparent location with an unseen hand (eg, under a table). (b) An experiment with stimuli on a frontoparallel plane in most cases does not test the different predictions based on Porterfield's axiom and Wells's propositions. Two or more stimuli are usually needed at different distances for the competing hypotheses to make different predictions. (c) When monocular stimuli are presented with binocular stimuli on the same frontoparallel plane, however, the prediction from Wells can be tested. When a fixation disparity is produced by underconvergence, the visual directions of the monocular stimuli seen with the right (left) eye are apparently displaced leftward (rightward) relative to the binocular stimulus. When it is produced by overconvergence, the visual directions of the monocular stimuli seen with the right (left) eye are apparently displaced rightward (leftward) (Nakamizo et al 2008).(5) (d) Even when a single spot of light is presented in the dark, the non-viewing eye has an effect on visual direction. The spot would be seen in its correct location only when the intersection of two visual axes remains on it. When the non-viewing eye deviates outward or inward, and thus changes the location of the common axis, the visual direction of the spot is displaced towards the direction of deviation (Mapp et al 2007; Ono and Gonda 1978; Ono and Weber 1981).

Third, the relative direction task in Khokhotva et al's (2005) experimental situation would not falsify or verify either hypothesis. For example, when two or more stimuli are collinear with respect to one eye (one slightly above the others so that they can be seen), an observer would judge the stimuli to be in the same direction. However, this judgment by itself does not tell us the direction in which the imaginary line passing through the stimuli appears to point. The headcentric judgment, as in Khokhotva et al or in the task described in (a) above, is required in order to determine whether the line appears to point to the eye, as predicted by Porterfield's axiom. If such a judgment were required while viewing the stimuli with only the eye to which the stimuli are aligned, an observer would judge the line to appear to point to the nose as predicted by Wells's Proposition I. With two eyes, an observer would judge the line to appear in two places; one to point to the nose as predicted by Proposition I and the other to point to an ear or outside of the face as predicted with Proposition III. See the Appendix for Proposition III and figure A1 for an example of a prediction from it.

2.5 *Speculation on the long survival of Porterfield's axiom*

The results derived from relative direction tasks, however, might explain the long survival of theories based on optics and projection. Because a relative direction task can be performed with a high degree of precision, as claimed by Young (1801) or more recently by Ono et al (2003), the writers of the seventeenth to the mid-nineteenth centuries (with the exception of Wells) may not have considered headcentric direction. To check, for example, whether a ruler is straight or whether three nails on a board are in line, one would use one eye, and a judgment can easily be made without attending

(5) Nakamizo et al (2008) used a set of vertical parallel lines for their stimulus, but not all the monocular stimuli presented followed the predictions of Wells (1792). The predictions failed when a monocular line was embedded in (Domini and Braunstein 2001; Erkelens and van Ee 1997a, 1997b; Ono and Mapp 1995; Shimono and Wade 2002; Shimono et al 1998, 2005, 2007) or when the monocular stimuli were placed in front of a monocular random-dot field (Erkelens 2000; Ono et al 2007). For a discussion of these failures, see Mapp et al (in press).

to their headcentric locations. In fact, headcentric direction can be ignored completely in a relative-direction task. Porterfield and others who advocated the projection theory followed Kepler (1604, 1611), who described how light was refracted through the structures of the eye and brought to a focus on the retina and Scheiner (1619), who gave a clear description and illustration of the gross anatomy of the eye. When the optics of image formation were understood, perhaps it was difficult to think that a retinal image can provide the perception of an incorrect direction. It is likely that this understanding gave Porterfield and Brewster the confidence to label their idea an 'axiom' and a 'law', respectively.

The difference between the two tasks relates to the information required to perform them successfully (Ono et al 2003). For a headcentric direction task, information about the retinal image locations as well as that of two eye positions are required. For a relative-direction task, on the other hand, only information about the relative retinal image positions is required. Because information about the eye position relative to the head is not used in a relative-direction judgment, the results from a relative-direction task have no relevance for a headcentric task. In the light of this distinction, the projection or optic theory is valid only with respect to judgments of relative visual direction (ie whether an object appears in the same direction, to the left, or to the right of another object). However, the prediction from the theory—that an object appears on its visual line—is invalid unless the object is located on the horopter.

It could be that neglecting the somewhat subtle distinction between headcentric and relative direction is responsible for the persistence of old ideas based on optics and projection. There are current claims that monocularly seen objects are veridically localised (Erkelens 2000; Erkelens and van de Grind 1994; Erkelens and van Ee 2002; Erkelens et al 1996; Khan and Crawford 2001; cf Mapp et al 2007; Ono et al 2002, 2007). All these researchers who claimed the veridicality used relative visual direction tasks, and therefore inferences about the origin of visual direction, an eye, or the cyclopean eye, cannot be made. (For a more detailed discussion of the distinctions and these recent studies, see Mapp et al 2002; Mapp et al, in press; Ono et al 2003.)

3 Conclusion

It is now 400 years since Kepler transformed the study of vision by describing the image-forming properties of the eye. Throughout this time the erroneous idea that an object seen with one eye always appears where it is as was claimed by Porterfield (1737, 1738) and others has remained undisputed, despite the fact that such veridicality is only true for objects on the horopter. Objects in front of or behind the fixation points that do not fuse was mislocalised regardless of whether they are seen with one eye or two. In contrast to Brewster's (1844a) claim that "Properly speaking, there is no such thing as a law of visible direction in binocular vision" (page 354), we claim that, properly speaking, there is no such thing as a law of visual direction for monocular stimuli. Even when a single stimulus is seen monocularly, the non-viewing eye and the viewing eye together determine the location of the common axis and determine the visual direction of the stimulus. Usually, it is not seen in its veridical location because the visual axis of the non-viewing eye deviates away from the stimulus. More generally, the direction of mislocalisation is determined by the location of the intersection of two visual axes and which eye views a non-fused stimulus. One of the diplopic images seen with the right (left) eye and closer than the intersection is apparently shifted leftward (rightward); one of the diplopic images seen with the right (left) eye and further than the intersection is apparently shifted rightward (leftward). The apparent shifts are in accordance with Wells's propositions and consistent with Porterfield's observation about which diplopic image disappears when one of the eyes is closed for the stimuli shown in figure 2. Applying the concept that became an integral part of understanding visual direction after Wells by Towne, Hering, and LeConte, we assert that we see as though from a central eye, the double eye, or the cyclopean eye even when we see with only one eye. The full implications of challenging the long-held and one-eyed view of visual direction have yet to be realised.

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References

Aguilonius F, 1613 *Opticorum Libri Sex. Philosophis juxta ac Mathematicis utiles* (Antwerp: Moretus)

Alhazen, 1572 *Opticae Thesaurus* Ed. F Risner (Basel: Gallia)

Berkeley G, 1709 *An Essay towards a New Theory of Vision* (Dublin: Pepyat)

Brewster D, 1830 *Optics* volume 15 *Edinburgh Encyclopædia* (Edinburgh: Blackwoods) pp 460 – 662

Brewster D, 1844a "On the law of visible position in single and binocular vision, and on the representation of solid figures by union of dissimilar plane pictures on the retina" *Transactions of the Royal Society of Edinburgh* **15** 349 – 368

Brewster D, 1844b "On the knowledge of distance given by binocular vision" *Transactions of the Royal Society of Edinburgh* **15** 663 – 674

Donahue W H, 2000 *Johannes Kepler. Optics: Paralipomena to Witelo & Optical Part of Astronomy* (Santa Fe, NM: Green Lion Press)

Domini F, Braunstein M L, 2001 "Influence of a stereo surface on the perceived tilt of a monocular line" *Perception & Psychophysics* **63** 607 – 624

Emsley H H, 1977 *Visual Optics* volume 1, 5th edition (Butterworths: London)

Erkelens C J, 2000 "Perceived direction during monocular viewing is based on signals of the viewing eye only" *Vision Research* **40** 2411 – 2419

Erkelens C J, Ee R van, 1997a "Capture of visual direction: an unexpected phenomenon in binocular vision" *Vision Research* **37** 1193 – 1196

Erkelens C J, Ee R van, 1997b "Capture of the visual direction of monocular objects by adjacent binocular objects" *Vision Research* **37** 1735 – 1745

Erkelens C J, Ee R van, 2002 "The role of the cyclopean eye in vision: sometimes inappropriate, always irrelevant" *Vision Research* **42** 1157 – 1163

Erkelens C J, Grind W A van de, 1994 "Binocular visual direction" *Vision Research* **34** 2963 – 2969

Erkelens C J, Muijs A J M, Ee R van, 1996 "Binocular alignment in different depth planes" *Vision Research* **36** 2141 – 2147

Gogel W C, 1972 "Depth adjacency and cue effectiveness" *Journal of Experimental Psychology* **92** 176 – 181

Gulick W L, Lawson R R, 1976 *Human Stereopsis: Psychophysical Analysis* (New York: Oxford University Press)

Hering E, 1868/1977 *The Theory of Binocular Vision* English translation by B Bridgeman, Eds B Bridgeman, L Stark (New York: Plenum Press)

Hering E, 1879/1942 *Spatial Sense and Movements of the Eye* English translation by C A Radde (Baltimore, MD: American Academy of Optometry)

Howard I P, 1996 "Alhazen's neglected discoveries of visual phenomena" *Perception* **25** 1203 – 1217

Howard I P, Rogers B J, 2002 *Seeing in Depth* Volume II *Depth Perception* (Toronto: Porteous)

Howard I P, Wade N J, 1996 "Ptolemy's contributions to the geometry of binocular vision" *Perception* **25** 1189 – 1201

Kepler J, 1604 *Ad Vitellionem Paralipomena* (Frankfurt: Marinium and Aubrii; translated in Donahue 2000)

Kepler J, 1611 *Dioptrice* (Augsburg: Franci)

Khan A Z, Crawford J D, 2001 "Ocular dominance reverses as a function of horizontal gaze angle" *Vision Research* **41** 1743 – 1748

Khokhotva M, Ono H, Mapp A P, 2005 "The cyclopean eye is relevant for predicting visual direction" *Vision Research* **45** 2339 – 2345

LeConte J, 1871 "On some phenomena of binocular vision; The mode of representing the position of double images" *American Journal of Science* **1** 33 – 44

LeConte J, 1881 *Sight: An Exposition of the Principles of Monocular and Binocular Vision* (New York: Appleton)

Lejeune A (Eds), 1956 *L'Optique de Claude Ptolémée dans la version Latine d'après l'Arabe de l'Émir Eugène de Sicile* (Louvain: Université de Louvain)

Mach E, 1921/1926 *The Principles of Physical Optics. An Historical and Philosophical Treatment* English translation by S Anderson, A F A Young (London: Methuen)

Mapp A P, Ono H, 1986 "The rhino-optical phenomenon: ocular parallax and the visible field beyond the nose" *Vision Research* **26** 1163 – 1165

Mapp A P, Ono H, Howard I P, 2002 "Binocular visual direction", in *Seeing in Depth* volume 2 *Depth Perception* Eds I P Howard, B J Rogers (Toronto: Porteous Publisher) pp 85 – 99

Mapp A P, Ono H, Howard I P, in press "Binocular visual direction", in *Seeing in Depth* volume 2 *Depth Perception* Eds I P Howard, B J Rogers (London: Wiley)

Mapp A P, Ono H, Khokhotva M, 2007 "Hitting the target: Relatively easy, yet absolutely impossible?" *Perception* **36** 1139 – 1151

Nakamizo S, Kawabata H, Ono H, 2008 "Misconvergence causes apparent displacement of the monocularly seen segment of a vertical line" *Japanese Psychological Research* **51** 49 – 62

Ono H, 1981 "On Wells's (1792) law of visual direction" *Perception & Psychophysics* **30** 403 – 406

Ono H, Gonda G, 1978 "Apparent movement, eye movement and phoria when two eyes alternate in viewing a stimulus" *Perception* **7** 75 – 83

Ono H, Lillakas L, Mapp A P, 2003 "The making of the direction sensing system for the Howard eggmobile", in *Levels of Perception* Eds L Harris, M Jenkin (New York: Springer Verlag) pp 127 – 147

Ono H, Mapp A P, 1995 "A restatement and modification of Wells – Hering's law of visual direction" *Perception* **24** 237 – 252

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

Ono H, Mapp A P, Mizushina H, 2007 "The cyclopean illusion unleashed" *Vision Research* **47** 2067 – 2075

Ono H, Weber E V, 1981 "Nonveridical visual direction produced by monocular viewing" *Journal of Experimental Psychology: Human Perception and Performance* **7** 937 – 947

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

Porterfield W, 1738 "An essay concerning the motions of our eyes. Part 2. Of their internal motions" *Edinburgh Medical Essays and Observations* **4** 124 – 294

Reid T, 1764 *An Inquiry into the Human Mind, on the Principles of Common Sense* (Edinburgh: Millar, Kincaid & Bell)

Sabra A I (Editor and Translator), 1989 *The Optics of Ibn al-Haytham, Books I – III. On Direct Vision* (London: The Warburg Institute)

Scheiner C, 1619 *Oculus, hoc est fundamentum opticum* (Innsbruck: Agricola)

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

Shimono K, Tam W J, Askaura N, Ohmi M, 2005 "Localization of monocular stimuli in different depth planes" *Vision Research* **45** 2631 – 2641

Shimono K, Tam W J, Ono H, 2007 "Apparent motion of monocular stimuli in different depth planes" *Vision Research* **47** 1027 – 1035

Shimono K, Wade N J, 2002 "Monocular alignment in different depth planes" *Vision Research* **42** 1127 – 1135

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)

Smith A M, 2001 *Alhazen's Theory of Visual Perception* (Philadelphia, PA: American Philosophical Society)

Smith R, 1738 *A Compleat System of Opticks in Four Books* (Cambridge: Published by the author)

Towne J, 1866 "Contributions to the physiology of binocular vision—Section VII" *Guy's Hospital Reports* **12** 285 – 301

Tyler C W, 1997 "On Ptolemy's geometry of binocular vision" *Perception* **26** 1579 – 1581

Wade N J, 1983 *Brewster and Wheatstone on Vision* (London: Academic Press)

Wade N J, 2003 *Destined for Distinguished Oblivion: The Scientific Vision of William Charles Wells (1757 – 1817)* (New York: Kluwer/Plenum)

Wade N J, 2007a "Image, eye, and retina" *Journal of the Optical Society of America A* **24** 1229 – 1249

Wade N J, 2007b "The vision of William Porterfield", in *Brain, Mind, and Medicine: Essays in 18th Century Neuroscience* Eds H Whitaker, C U M Smith, S Finger (New York: Springer) pp 163 – 176

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

Wade N J, Swanston M T, 2001 *Visual Perception: An Introduction* 2nd edition (Hove: Psychology Press)
Wells W C, 1792/2003 *An Essay upon Single Vision with Two Eyes: Together with Experiments and Observations on several other Subjects in Optics* (London: Cadell) reprinted in Wade 2003
Wheatstone C, 1838 "Contributions to the physiology of vision—Part the first. On some remarkable, and hitherto unobserved, phenomena of binocular vision" *Philosophical Transactions of the Royal Society of London* **128** 371 – 394
Young T, 1801 "On the mechanism of the eye" *Philosophical Transactions of the Royal Society of London* **91** 23 – 88

Appendix

Figures A1 and A2 illustrate the predictions by Porterfield, Wells, and Towne/Hering/LeConte for Porterfield's figures 4 and 5. Wells's predictions in figures A1 and A2 are based on his Proposition III, which states: "Objects, situated in any Line drawn through the mutual Intersection of the Optic Axes to the Visual Base, do not appear to be in that Line, but in another, drawn through the same Intersection, to a Point in the Visual Base distant half this Base from the similar Extremity of the former Line, towards the left, if the objects be seen by the Right Eye, but towards the right, if seen by the Left Eye" (1792, page 50). Propositions I and II are special cases of Proposition III. Proposition I deals with a stimulus on one of the visual axes and Proposition II with a stimulus on the common axis.

According to Wells (1792) Porterfield had "done little more than copy what he [Aguilonius] has said" (1792, page 4). Wells wrote the following against Aguilonius's (therefore also against Porterfield's) idea of diplopic images being 'referred' to the horopter and being seen double.

> "Against the truth of this explanation, only one argument need be offered. Were the visible places of all bodies to be contained in the plane of the horopter, these would appear of magnitudes proportional to the angles which they subtend at the eye. A finger, for instance, held near to the face, would seem as large as the part of a remote building it might conceal from the sight. But as this is contrary to experience, the principle from which it is derived, must be rejected, together with all its consequences. To Aguilonius, however, the merit is due, of being the first who so far generalized the phenomena of single and double vision, as to observe, that those objects alone are seen single, which are really situated in the plane of the horopter." (Wells 1792, pages 5 – 6)

The first part of this statement is very similar to an observation made by George Berkeley (1709) as evidence against visual size being determined by visual angle: "Hence, it's evident, one in those Circumstances would judge his Thumb, with which he might hide a Tower, or hinder its being seen, equal to that Tower, or his Hand, the Interposition whereof might conceal the Firmament from his View, equal to the Firmament" (page 94). However, unlike Berkeley, Wells (1792) made a clear distinction between visual direction and visual distance. Wells hypothesised that visual direction is processed with an innate mechanism (by 'nature') and that visual distance is processed by an acquired mechanism (by 'custom'). Consistent with this hypothesis, he stated that "In judging of distance by sight, we frequently make considerable mistakes, even when the objects are not very remote; ..." (page 35) and went on to state "I do not stop to give the reason of this fact, which must be plain to those who are acquainted with Bishop Berkeley's theory of visible distance..." (page 36). Berkeley did not dwell on the mistakes that are made in judging distance, but he did dispel arguments that perception was a consequence of 'natural geometry' in which lines and angles are used to determine distance and magnitude. He inveighed against the dominant analysis of vision in terms of optics and Wells found considerable sympathy with this position.

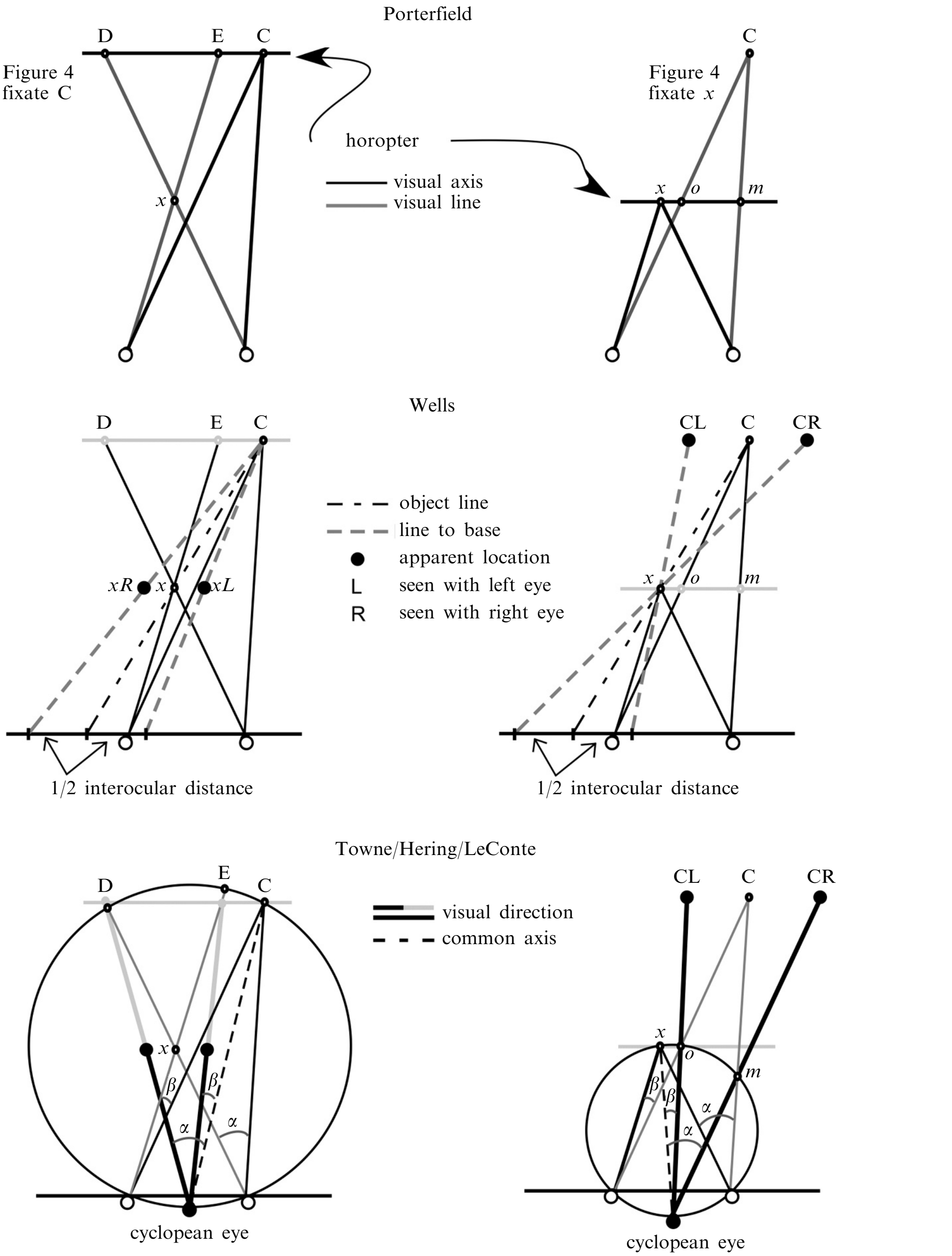

Figure A1. Predictions for Porterfield's figure 4 by Porterfield, Wells, and Towne/Hering/LeConte. Wells's prediction is based on his Proposition III (see text). For Hering's prediction, refer to the caption for figure 3.

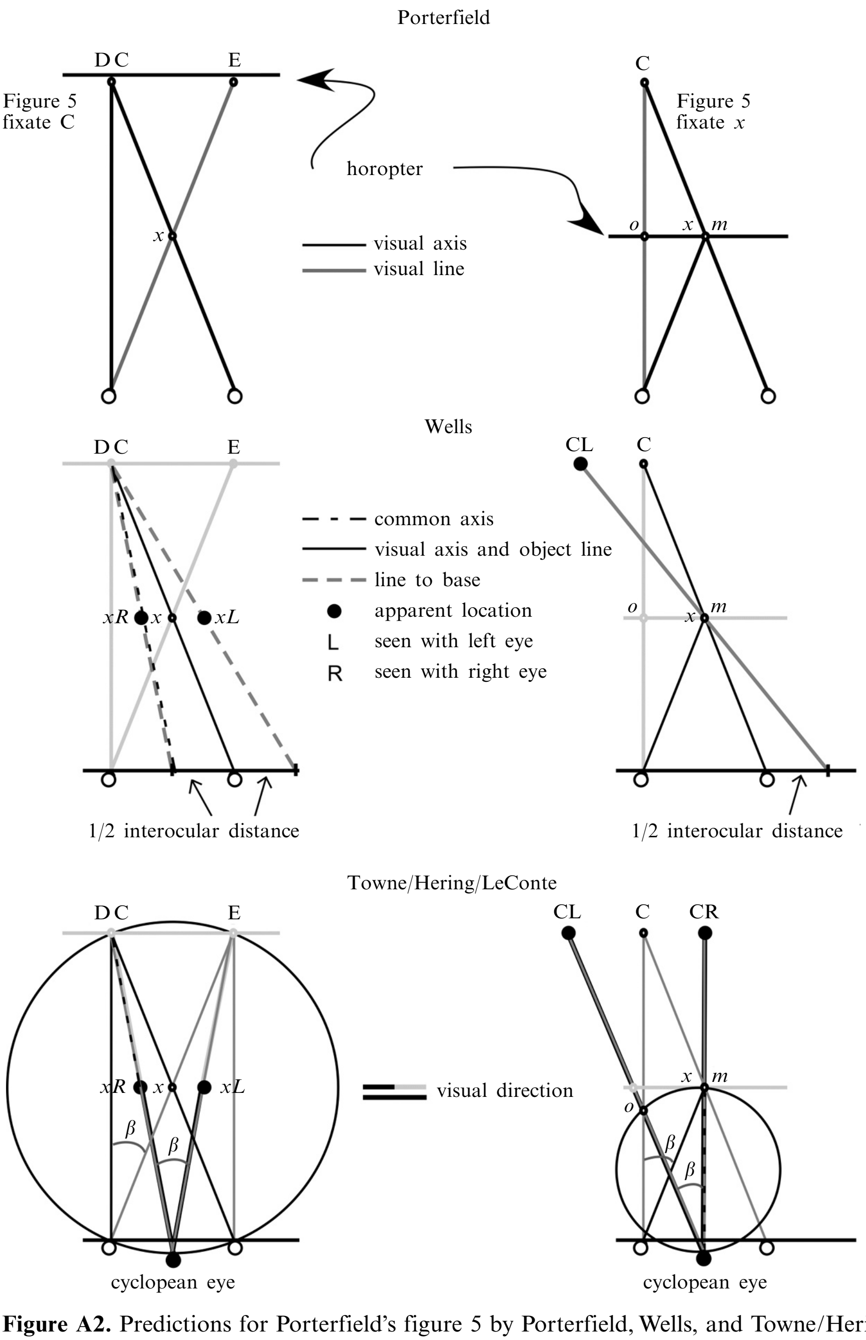

Figure A2. Predictions for Porterfield's figure 5 by Porterfield, Wells, and Towne/Hering/LeConte. Wells's prediction is based on his Proposition III (see text) and Proposition I: "Objects, situated in the Optic Axis, do not appear to be in that Line, but in the Common Axis" (1792/2003, page 40). For Hering's prediction, refer to the caption for figure 3.

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