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The role of the cyclopean eye in vision: sometimes inappropriate, always irrelevant

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Abstract

During binocular fixation, the eyes usually point in different directions, and yet, each object is judged to lie in a single direction. It is commonly believed that a particular location in the head serves as the origin for such directional judgments. This location is known as the cyclopean eye. We argue here that observers can judge visually perceived directions from angular information alone, and do not require positional information supplied by a cyclopean eye. We show that experimental findings reported as evidence for the cyclopean concept can also be explained solely by angular information without the need for a cyclopean eye. Recent findings concerning binocular shape perception and the cyclopean illusion demonstrate that binocular perception is incompatible with vision from a single vantage point. The concept of the cyclopean eye is sometimes inappropriate and always irrelevant as far as vision is concerned. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Binocular vision; Depth; Direction

1. Introduction

The laws of visual direction (reviewed by Ono (1991) and Howard and Rogers (1995)) describe the method by which the visual system estimates the directions of binocular targets. This method formulated originally by Alhazen, Wells, and Hering, and consolidated by Ono and others is often referred to as Hering's laws of visual direction (Hering, 1942). According to these laws, the perceived headcentric direction of a target is based on the headcentric fixation direction (visual axis) of either eye and the oculocentric target direction (visual line) in either eye. [1] It is important to stress that only angular (but not positional) measures are involved in this scheme.

One of Hering's laws, the law of common binocular direction, states that the directions derived from the two eyes' images will be perceived as if the observer is viewing the scene from a single vantage point between the two eyes. This point is called the cyclopean eye (a name coined by von Helmholtz (1962)). [2] According to Hering (1942), the cyclopean eye is located in the median plane on the Vieth–Müller circle. Ono (1991) concluded that a position midway between the two eyes was a reasonable working hypothesis. Recently, Mapp and Ono (1999) have gone so far as to assert that the cyclopean eye is both a logical and a functional necessity for judging the directions of objects.

In this paper we will first review the observations that have led to the postulation of the cyclopean eye and then we will go on to review two main methods that have been used to locate the cyclopean eye. We will show that these observations and results from visual tasks used to locate the cyclopean eye can be understood without the need to postulate a cyclopean eye. In other words we dispute Mapp and Ono's claim that the cyclopean eye is a logical necessity for judging the directions of objects. From a mathematical point of view, the location of the cyclopean eye does not have any effect on binocularly perceived directions. Visually perceived directions depend on the retinal loci as well as on the orientations of

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[1] Note that the generally used term "visual direction" denotes an entity in the perceptual domain, whereas "visual line" and "visual axis" are physical entities. To avoid any confusion we use the terms "perceived direction" or "visually perceived direction".

[2] Julesz (1971) used the term "cyclopean" to indicate central processing. In the earlier definition of Helmholtz and Hering it indicates a central location.

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the eyes, and thus, on angular measures which require directions (not positions) as references. We will demonstrate that only motor tasks such as pointing and heading require a positional reference.

In addition, we will argue not only that binocular vision can be understood without a cyclopean eye but also that there are situations where the cyclopean eye concept is inappropriate to describe binocular vision. It gives rise to paradoxes in binocular viewing of typical three-dimensional (3D) scenes when objects are partly occluded by closer objects.

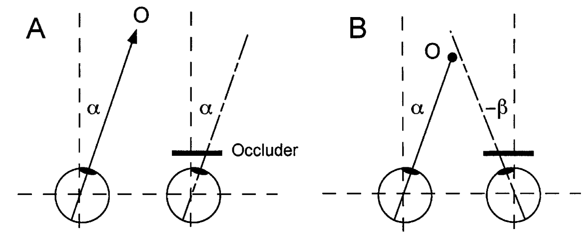

Fig. 1. The cyclopean illusion (Hering, 1942). Changing fixation from infinity (A) to a nearby position (B) without changing the position of the retinal image of an object O changes the visually perceived direction of O.

2. The postulation of the cyclopean eye as a single visual sensor

Two observations gave rise to the postulation of the cyclopean eye. In the first observation, Hering's observation, the viewer holds the head steady and the left eye fixates a distant tree while the right eye is closed. A black spot, physically located in front of the nose on a pane of glass nearer than the tree, is aligned with the tree. When the right eye fixates the spot while the left eye is closed, a distant house is in line with the dot. When both eyes fixate the spot, the house and the tree appear aligned in the same, straight-ahead direction. Hering interpreted this finding as if the house and the tree were viewed from a single location, the cyclopean eye. However, if we apply Hering's rules of perceived direction we find that the straight-ahead direction of the spot, house and tree simply follows from combining physical angles. It follows directly from Hering's rule of identical visual direction that objects are perceived in the same, straight-ahead direction when they are fixated (by either eye or both eyes) in symmetrical convergence. Hering used the cyclopean eye as nothing more than a descriptive vehicle to account for this particular observation. However, it is important to note that by opting for the cyclopean eye as the locations where the angles are added together he took an irrelevant step. From a mathematical point of view, Hering could have chosen any other location for the addition of angles. Translating vectors, in this case visual lines and visual axes, to a common point does not change the direction of the vectors (a mathematical fact). The fact that we see the tree and house aligned simply means that we see them in the same direction. It does not mean that we see them from a single location.

The second observation, called the cyclopean illusion (Hering, 1942), is illustrated in Fig. 1. Consider a situation in which the left eye fixates an object O at infinity (A). Suppose now that O approaches the viewing left eye (B). An illusory movement of O to the left is then observed. Hering (1942) concluded that the visually perceived direction of O was indicated by its retinal locus in the left eye and the orientation of both the left and the right eyes. Hering's laws state that when O approaches the observer in the direction of the left eye (so that the angle α remains constant; Fig. 1) and the right eye responds by a leftward rotation, the perceived direction of O will change from α to $(\alpha + \beta)/2$ (the mean direction of the two visual axes; Fig. 1) which in this example is associated with a leftward change in the visually perceived direction of O. Note that a positional reference is not taken into account.

Thus, the visually perceived directions in these demonstrations are described fully by angular information. As far as we know, all observations concerning perceived directions can be explained by an analysis of directions alone, there is no need to make any assumptions about the location of the cyclopean eye. [3] It is worth noting that the argument that the two eyes always act as a single sensor was recently falsified by experiments in which perceived directions were judged during monocular viewing of full-field scenes in daylight conditions (Erkelens, 2000). The experiments showed that the cyclopean illusion was absent during monocular viewing, the visually perceived directions of objects were indicated by their retinal locus in combination with the orientation of the viewing eye only, the orientation of the closed eye being irrelevant.

3. The location of the cyclopean eye

Several procedures (reviewed and compared by Mitson, Ono, and Barbeito (1976)) have been used to determine the location of the cyclopean eye. Central in

[3] In textbooks a misleading illustration (Fig. 2) is frequently used to demonstrate that visually perceived directions are referred to the cyclopean eye. The illustration shows a person just looking over a horizontally placed piece of cardboard. On the card two lines are drawn from a common point, which has to be fixated by the viewer, to the pupils of the viewer's eyes. The two lines are perceived as a single line in the median plane of the head. Inspection of the retinal images easily reveals the misleading nature of the illustration. If the two lines are oriented along visual lines, their retinal images are dots. If the two lines are not oriented along visual lines, their retinal images are lines which may contain disparity, perspective and accommodative cues. Without these cues the viewer would see a line in the frontal plane.

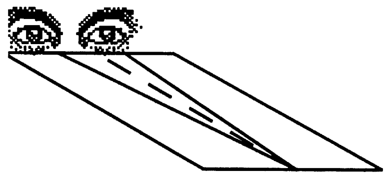

Fig. 2. A misleading illustration of the cyclopean eye. Each line has to point to the pupil of an eye, and fixation should be at the points where the lines meet. However, the lines would be viewed as dots if viewers would accurately follow these instructions. The two lines appear superimposed in the straight-ahead direction if the eyes are positioned just above the lines. However, then the retinal images are vertical lines instead of dots as the retinal images of visual lines would be.

these procedures was that subjects were asked to align oblong objects (or two objects) so that the objects (or the line connection the objects) pointed at the subjects themselves (Howard & Templeton, 1966). A variant of the task was that subjects had to indicate where such objects would hit their face, if these objects would have moved along their long axis (Roelofs, 1959). We believe that the visual sensation that is felt when something is "pointing at you" has been wrongly interpreted as a feeling that something is "pointing at a specific part of the body". It is much more likely that the sensation pointing at you is not associated with pointing at a specific *position* but with pointing *along a visual direction.* Fig. 3 shows six physically present arrows in the horizontal plane, visible to an observer in either monocular or binocular viewing. Experiments have shown that objects oriented in the directions of the arrows induced the sensation pointing at you. In monocular viewing (Fig. 3A) the objects were physically aligned with the viewing eye (Roelofs, 1959). In binocular viewing (Fig. 3B) the objects were physically aligned with a location between the two eyes (Howard & Templeton, 1966). The six arrows have in common that they are oriented along visually perceived directions which means that the heads and tails appear to be aligned, or superimposed. In monocular viewing this situation occurs when the arrows are pointing toward the nodal point of the viewing eye. In binocular viewing the situation is slightly different. In binocular viewing only one detail, for instance the head of the arrows, is seen in a single visual direction. Then the tails are seen in two different directions, one originating from the left eye's view and the other from the right eye's view. There is one orientation of the arrows at which the visual directions of the tails are centred about the visual directions of the arrowheads. In this orientation the head and the tail of the arrows have the same *mean* visually perceived direction (Fig. 3B). In binocular viewing the arrows are pointing towards a location halfway between the two eyes when the eyes are balanced (both eyes contribute equally to the mean). If one of the eyes is dominant, the location is shifted towards the dominant eye (Barbeito, 1981; Barbeito & Simpson, 1991). In conclusion, in monocular and binocular viewing the sensation pointing at you (a perceptual quality) can be either associated with the perceptual attribute "oriented along a visual direction" or with a non-visible point of convergence of visually perceived directions. It is most likely that the attribute oriented along a visual direction causes the sensation pointing at you because the visual system measures it directly with high precision. The invisible point of convergence, the cyclopean eye, can only be estimated indirectly by methods of geometrical reconstruction or inference.

It is helpful to divide the procedures that have been used to determine the location of the cyclopean eye according to the types of tasks they employed: visual, visuo-motor, and motor tasks. In cyclopean eye experiments, visual tasks are defined as tasks in which the subjects respond by non-spatial motor responses (for instance by giving answers or pressing a key on the computer keyboard). Motor tasks are tasks in which the subjects give spatial motor responses, such as pointing to a certain location, on condition that the responses do not interfere with the visual stimulus. Visuo-motor tasks

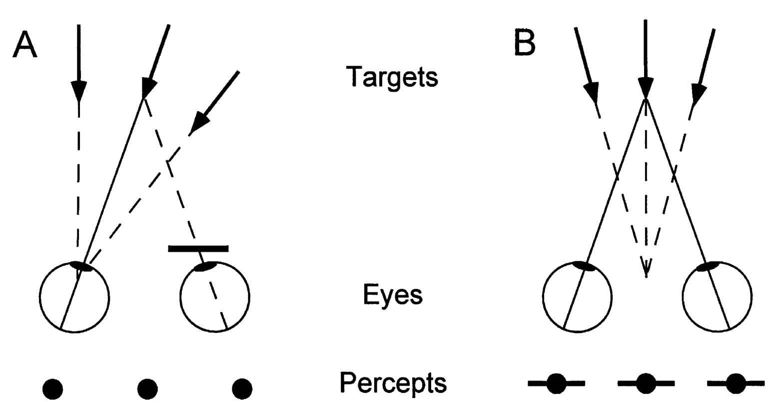

Fig. 3. Top view of six physical arrows (targets). Each arrow is perceived to be pointing at the observer. Viewing is with the left eye in (A), viewing is with both eyes in (B). The dots (percepts) give a schematic impression of how the observer perceives the arrows.

are tasks in which the subjects give spatial motor responses that interfere with the visual stimulus.

In the visual task proposed by Howard and Templeton (1966) and refined by Mitson et al. (1976), two stimuli were visible in the horizontal eye-level plane at different distances from the subject. The subject fixated the near and the far stimuli alternately and moved the near stimulus until the imaginary axis joining the two stimuli was judged to be pointing directly at the point from which the subject felt that the stimuli were viewed. This subjective point was found to coincide with the interocular axis midway between the two eyes. It was then concluded that the cyclopean eye was involved. Here too, no cyclopean eye is needed to explain the finding: On the basis of Hering's laws it is predicted that the visually perceived directions of the two targets are the average of the target's headcentric directions signalled by the two eyes (see Fig. 1 in van Ee, Banks, & Backus, 1999). Drawing a line between the two fixated targets will by definition lead to a point at which the line intersects with the interocular axis that is midway between the eyes. This task illustrates Hering's postulated averaging of headcentric directions from the two eyes, but the results have nothing to do with the cyclopean eye. 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 (Fig. 3A).

Dengis, Simpson, Steinbach, and Ono (1998) used results from a combined visuo-motor and motor task as evidence for the central location of the cyclopean eye. In this task subjects raised a hollow tube to their head with the intention of looking through it. Binocular subjects placed the tube approximately at the bridge of their nose if vision of the tube was suddenly blocked during the movement. In this task, subjects may just have finished a visually guided movement along a visually perceived direction to which the same reasoning applies as to the visual task: a line drawn in this direction that starts from the fixation point intersects the head at a point midway between the eyes.

It is essentially as a result of visuo-motor calibration that motor tasks can indicate visually directions and positions. Since the calibration of motor behaviour is such a key issue in both the correct and incorrect development of the cyclopean eye concept, we give an example that will illustrate its importance. Consider a thought experiment in which in front of the eyes one places a binocular periscope that effectively translates the visual axes of the two eyes together over a significant distance either to the left or to the right. The viewer is not allowed to have any knowledge of the magnitude of the shift and s/he is not allowed to see any part of his or her body. In this condition the viewer has no visual means of knowing either the magnitude or the direction of the shift. On the one hand, Hering's laws predict that on the basis of the above-described visual task the cyclopean eye will be located in between the apertures of the periscope, even if this location were to lie outside the head. On the other hand, measurements of the location of the cyclopean eye that are based on motor tasks will still reveal the location to be close to the bridge of the nose as long as the viewer is not allowed to see his or her arm. Thus, the important point here is that visual and motor tasks will provide different locations for the cyclopean eye, which illustrates that the tasks are based on different sources of information. Now, suppose that the subject's arm becomes visible. Due to visual feedback, visuo-motor calibration will be affected by the presence of the periscope. It is likely that over time measurements of the cyclopean eye based on motor tasks will gradually become more and more consistent with the location of the periscope (this prediction is supported by the finding that in monocularly enucleated people the cyclopean eye shifts toward the remaining eye). The important conclusion that follows from this example is that motor tasks can only reliably indicate those visual positions and directions that are subject to visuo-motor calibration. The cyclopean eye, however, is a perceptual entity that is not represented in the visual space. There is no error signal that can calibrate the motor responses. Therefore motor tasks are not suited to indicate the location of the cyclopean eye.

4. When is a calibration point necessary?

Although the cyclopean eye does not affect visually perceived directions, the adaptation of hand movements to, for instance, the wearing of prisms supports the claim that a positional reference is indeed relevant for calibrating motor commands to the visual representation of space. Goal-directed actions require directional information about the target relative to a particular part of the body. For instance, a soccer player has to know where to place his foot and in what direction to kick a moving ball towards the goal if the foot and goal are not visible at the same time. The location of this reference, e.g. the bridge of the nose, the heart, the brain, or hara, is likely to be based on cultural differences and might also be task dependent.

Consider the well-known pointing experiments in which subjects wear prisms. In such experiments subjects are asked to point a forefinger at a visible target. When pointing is performed by an unseen finger subjects make systematic directional errors. In other words, the finger movements are not correctly calibrated to the perceived directions. Making the forefinger visible, changes the pointing direction of the finger gradually so that after a couple of trials pointing is correct again. However, this gradual change in pointing direction does not change visually perceived directions. An object that is judged to be straight ahead if the finger is not visible remains straight ahead after the finger has become visible. Finger pointing remains correct after the finger is made invisible. However, after the prisms are removed, pointing with an unseen finger is once again inaccurate and again it takes a couple of trials before pointing is the same as it was before the experiment was conducted. Apparently, in the course of this experiment we interpret learning to point correctly as changing the calibration of our motor behaviour in response to unchanged perceived directions. Obviously, this recalibration procedure involves a positional reference, but the recalibration does not affect the perceived directions.

5. When is the cyclopean eye concept inappropriate?

The concept of the cyclopean eye gives rise to an interesting paradox (Erkelens & van de Grind, 1994; van Ee & Erkelens, 2000) that has long gone unnoticed. The cyclopean as well as the real eyes have the structure of two-dimensional (2D) manifolds on which each position represents a direction. In typical 3D scenes, one eye will view a number of details that are not visible to the other eye. The cyclopean eye can only accommodate all monocularly visible details if it has room for more directions than either eye. Nevertheless, experimental results have shown that all the monocularly visible elements of the visual scene are also represented in the stereoscopic percept of the scene (Erkelens, Muijs, & van Ee, 1996; Erkelens & van Ee, 1997a,b; Lillakas, Ono, & Grove, 1998; Ohtsuka & Ono, 1998). There are two possible ways in which the cyclopean eye can accommodate the regions that are visible to either eye. Either visual space becomes distorted or it cannot be divided into independent perceived directions and distances.

Ohtsuka and Ono (1998) proposed a mechanism that, perceptually, both displaces and compresses a portion of the visual field in the horizontal direction. (Indeed this would be a solution that fits all directions into a 2D cyclopean eye.) They suggested that the Poggendorff and Kanizsa illusions are explained by such a mechanism. However, van Ee and Erkelens (2000, Fig. 4) demonstrated that both illusions are essentially 2D phenomena. In the same study we also examined whether stereoscopically perceived shapes can be based on comparison of visually perceived directions. We found that observers did not perceive the distortions of the aspect ratios of partially occluded rectangles that were predicted on the basis of the comparison of perceived directions of their edges. We conclude from this finding that our stereoscopic shape perception is not based on a spatial representation that can be divided into 2D directions and one-dimensional distances relative to the observer. In other words, our perception of forms does not seem to be based on an egocentric representation.

Mainly for two reasons binocular perception cannot be regarded as monocular perception from the vantage point of the cyclopean eye. Firstly, the binocular percept contains details that would not be visible to a single eye. Secondly, shape and alignment are incompatible in binocular vision. Apparently, they follow from different representations. As a consequence the cyclopean eye is an inappropriate concept for binocular perception.

6. Discussion

We have reviewed the observations that have led to the postulation of the cyclopean eye as well as the two main methods that have been used to locate the cyclopean eye. We have argued that the alleged findings concerning the existence of the cyclopean eye can be understood without postulating a cyclopean eye. The metaphor of the cyclopean eye assumes two properties of binocular vision: (1) binocular perception requires a reference point in the head and (2) binocular perception is identical to monocular perception from a different vantage point. On the basis of theoretical considerations and recent experimental findings we have concluded that both assumptions are false.

It should be stressed that we do not claim that the concept of the cyclopean eye should never be used, only that it is not suited to understand binocular vision. It is of course possible to use an imaginary location like the cyclopean eye as a mathematical vehicle so that the combination of vectors (visual axes and visual lines) becomes more intuitive. Although it is not wrong to do this, the location itself is irrelevant as far as vision is concerned. Mapp and Ono (1999), unfortunately, went a step further: they claimed mistakenly that the cyclopean eye is needed to judge the perceived directions of objects. As we have shown, the location of the cyclopean eye does not have any effect on binocular vision: visually perceived directions depend on the retinal loci as well as on the orientations of the eyes, and thus, on angular measures which require directions (not positions) as references. We have further demonstrated that the presence of a cyclopean eye gives rise to paradoxes in binocular viewing of typical 3D scenes when objects are partly occluded by closer objects. These paradoxes (and artificial ad hoc solutions) can be avoided if the cyclopean eye is not taken into account. When we interact with the environment in visuo-motor tasks a reference between the visual and motor spaces is obviously needed (although it may be hard to prove that one location will serve better as a reference than any other location).

A widespread misconception is that the cyclopean eye is essential for understanding eye movements. Hering (1942) formulated an important concept of eye movements in terms of "equal innervation". Irrespective of whether Hering's formulations are regarded as a description of eye movements or as a classification of eye movement control systems (Erkelens, Steinman, & Collewijn, 1989), a reference position such as the cyclopean eye is irrelevant in both interpretations. There are no models concerning the control of binocular eye movements that incorporate the cyclopean eye as a basic element. The reason is that inputs of the oculomotor control systems (e.g. retinal slip, retinal disparity) are angular measures and the outputs (e.g. smooth pursuit, vergence) are rotations about ocular axes. Incorrect terminology such as "eye positions" and "retinal positions", which is frequently used in the literature of binocular vision and eye movements, may have contributed to the confusion between directions and positions.

7. Conclusion

Mapp and Ono (1999) expressed the view that a point of reference, the cyclopean eye, is required for judging visual directions. We have argued that whereas a reference is *relevant* for motor tasks, it is *irrelevant* for visual direction tasks and *inappropriate* for binocular shape perception in typical 3D scenes.

Acknowledgements

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Addendum

Ono, Mapp and Howard (2001, this issue, p. ??; hereafter OMH) have responded to our challenging paper (Erkelens & van Ee, 2001, this article; hereafter EvE) with additional experimental results and a review of existing findings. What is the current status of the disagreement? Let us first consider the issues that OMH and EvE agree on. In OMH's own words, the cyclopean eye (CE): $\cdots$ "concept is not relevant for relative direction judgments, since these judgments require only information regarding the position of the object's retinal image(s)" (p??) *cdots* relative to other reference (or background) objects. OMH and EvE now also agree that "the distinction between visual and motor reference points may eventually provide a better understanding of how the visual system processes direction" (p??). Moreover, we agree that: "detailed experimental procedures to measure the constructs are needed as we have done for the distinction between absolute and relative direction in Expt 1" (p??). Note that the consequence of this latter statement is that a relatively large number of experiments (see OMH's citations) were apparently not adequate to affirm the long-standing empirical feeling that we view the world as if we view it from the CE.

Indeed we are astounded that results of many poor experiments from the literature carry so much weight. We have no reason, however, to question the many published accounts that there are circumstances in which we feel that we view the world from the CE. We question the methodological quality of existing experiments that were set out to affirm both the existence, and the location of the CE. In this regard we would like to refer to EvE's paper, in particular to our periscope thought experiment: Because the measured location of the CE will always fall in between the physical sensors (see EvE), the CE can easily fall outside the head while looking through the periscopes. There is no visual way to tell that the location of the CE changed after putting up the periscopes. It essentially depends on experience (knowing the locations of the eyes—or cameras) where people locate the CE. If one questions the validity of the periscope experiment to measure the location of the CE when the periscopes shift the visual world, one should also question the validity of an experiment where this shift equals zero (mimicking normal viewing).

We neither consider it to be a service to the reader to respond to the many interpretations, suggestions and speculations of OMH, nor do we think that this is the place to present a detailed account of the criticism concerning their experimental methodology. A few concerns need to be addressed though. Concerning OMH's first experiment, we leave it to the reader to objectively judge whether the paradigm in which subjects "were told to report where the near LED appeared to be, rather than where they knew it to be located" (p??) meets the psychophysical standards to unequivocally affirm the existence and the location of such an important and long-standing concept as the CE. (Note that in this experiment the subjects had to come off the biteboard to give their report. The distance of the near LED was only 20 mm. A translation of the head of ± 1 mm (after returning to the biteboard) would lead to a relatively large direction change of several degrees.) Concerning their second experiment, OMH discuss the eye movement results of four subjects and stress that a number of subjects make smaller eye movements during monocular viewing than during binocular viewing. Two subjects made hardly any eye movements and perceived no illusion. The absence of both the illusion and eye movements in these subjects does, however, neither falsify the hypothesis of Erkelens (2001) that perceived direction during monocular viewing is based on signals of the viewing eye only, nor does it affirm OMH's hypothesis that perceived direction during monocular viewing is based on signals of both eyes. Moreover, OMH do apparently not realize that there is one subject (DT) who actually contradicts their hypothesis: DT reported no illusion but exhibited considerable eye movements. Erkelens (2001) encountered another four of such subjects. The results of these five subjects (and just one would have sufficed) falsify the hypothesis that perceived direction during monocular viewing is based on signals of both eyes. Also, note that the two subjects who experienced the cyclopean illusion during monocular viewing reported a pivoting line near the face (p??), which was most likely caused by misalignment between the stimuli and the viewing eye. Misalignment and phoria would have been visible in the eye movement recordings if the authors had presented data for the individual eyes, as Erkelens (2001) did.

What disagreements do remain? We still argue against the claim that in vision "the CE is both a logical and a functional necessity for judging the directions of objects" (Mapp & Ono (1999)). All of the points raised by EvE do still apply. We argue that while a reference is relevant for motor tasks, it is irrelevant for visual direction tasks and inappropriate for binocular vision in typical three-dimensional scenes. Existing findings in binocular vision (and perceptual feelings) can be fully understood without a CE. Finally we challenge the reader to come up with independent solid evidence that cannot be explained solely by signals from the two eyes and that can only be explained by having a well-located CE.

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