Optic arrays and celestial spheres

In a recent editorial, Barbara Gillam (2007) argued the case for describing motion parallax and binocular stereopsis in terms of optic array rather than retinal image properties. J J Gibson’s concept of an optic array is based on a description of how light is structured at a particular vantage point, and it is expressed in angular terms. In order to make the concept and properties of the optic array easier to appreciate, Gibson typically used the technique of projecting the array onto a surrounding spherical surface (eg Gibson 1979, figure 7.3; and figure 1). Johansson and Börjesson (1989) used the same technique to illustrate the additional information for space perception that is available from wide-angle viewing. Gibson argued that the optic array conception was particularly useful because it allowed one to separate out the potential information that may be available in the optic array from the actual information that a particular visual system is able to extract, with all its limitations and particular mechanisms. For example, simple mathematics can be used to show that there is information in the expanding optic array to specify the time-to-contact between an observer and an approaching object, but this does not guarantee that any particular visual system will be able to use that information. I have found the optic array concept especially useful for thinking about binocular stereopsis, because the information for stereopsis arises precisely because we have two spatially separated vantage points (due to our spatially separated eyes) and hence the two optic arrays at those vantage points are different (figure 1; and Rogers 1993).

The optic array differences are logically prior, since, if there were no optic array differences, there could be no retinal disparities. Moreover, when the eye of a visual system is placed at a particular vantage point, it can be said to sample the optic array by making the appropriate eye (or head) movements. As a consequence, the characteristics...
of the retinal image are not the same as those of the optic array and these differences have been the source of several confusions in the past. The most notable example is whether the centre of outflow (or expansion) provides information about the direction of heading (Gibson 1979) or the direction of gaze (Regan and Beverley 1982). The centre of outflow in the optic array specifies the direction of heading (by definition), but it is important to remember that we do not have access to optic arrays—only to our own retinal images. The reason why the centre of outflow in the retinal image does not indicate the direction of heading is that our eyes can move. Typically, we fixate some close object when we move around in the world and, as a consequence, our eyes rotate to maintain fixation so that the fixated object becomes the centre of expansion in the retinal image rather than the point which we are approaching.

A similar confusion arose some 15 years ago when the late Mark Bradshaw and I started to investigate vertical disparities. According to Mayhew and Longuet-Higgins's (1982) elegant mathematical analysis, vertical disparities are said to provide information about the vergence distance of the eyes and the angle of eccentric gaze—the so-called $d/g$ hypothesis (Frisby 1984). However, if one thinks about the pattern of vertical disparities in the optic arrays created by a surface from two spatially separated vantage points (which we termed differential perspective), it is easy to show that the horizontal gradient of vertical disparities between the optic arrays provides information about the distance of a surface (Rogers and Bradshaw 1993) and tells us nothing about the vergence distance of the eyes. (Eyes do not come into an optic array description.) Mayhew and Longuet-Higgins's analysis, on the other hand, was based on the characteristics of binocular images projected onto flat camera planes. In this case, the gradient of vertical disparities does provide information about the vergence angle of the cameras. The confusion would never have arisen if we had realised the significance of differences between optic arrays and projected images.

J J Gibson introduced the idea of an optic array as part of his direct or ecological theory of perception, and he famously regarded the retinal image as being ‘unnecessary’ for visual perception (Gibson 1979, page 62). However, it turns out that Hermann von Helmholtz, the founder of the indirect or constructivist account of perception that Gibson wished to refute, actually proposed a rather similar idea. In the third volume of his Handbuch der Physiologischen Optik, Helmholtz (1867) made the distinction between the visual globe (Sehfeld) of the eye (which moves with the eye) and the field of fixation or celestial sphere (Blickfeld). The latter is not unlike Gibson’s idea of an optic array. He wrote “... the field of fixation may be regarded as a sphere of infinite radius, like a celestial dome, with its centre at the pivot of the eye” (page 164). One of the main reasons why Helmholtz introduced the idea of a celestial sphere was to provide a framework and coordinate system for describing eye movements. In particular, he proposed that eye movements were better described with a system in which the elevation of an eye is assessed first with reference to the equatorial plane of the celestial sphere before the azimuth is assessed with respect to an axis orthogonal to that elevated plane—the so-called ‘Helmholtz system’. This was in contrast to the previously described ‘Fick system’ in which azimuth is assessed first with respect to the sagittal plane of the celestial sphere before elevation is assessed with respect to an eccentric vertical plane (Howard and Rogers 1995). For Helmholtz, eye movements allowed the visual globe (Sehfeld) to sample the celestial sphere (Blickfeld), just as they do in Gibson’s optic array.

It is interesting to probe Helmholtz’s justification for talking about the visual globe rather than the retinal image. He wrote “I prefer to consider the two surfaces (the visual globe and the field of fixation) that are outside the eye rather than the retina and the retinal image, because the former are a more correct expression of our actual consciousness, and because by directly referring all places to the two spherical fields
we avoid the ambiguity that is responsible for so much that is erroneous here; whereas when we speak of knowing the positions of objects by the places on the retina that are affected by them, we seem to imply that we are aware of the retina and know something about its dimensions and extent” (Helmholtz 1910, page 166).\(^1\) In other words, what we see is an external visual world rather than our own retinal images. The reason for choosing a sphere of infinite radius was merely to simplify the geometry.

In addition, Helmholtz used his celestial sphere to try to answer the question of how we judge the straightness of lines in the world (see Rogers and Brecher 2007 for further details). He argued that, although straight lines in the visual world project to great circles on his celestial sphere, great circles were not the basis for judging straightness. Rather, he used the experimental evidence from a series of ingenious demonstrations to propose that ‘direction circles’—‘Richtkreise’ or ‘Direktionskreise’—on the celestial sphere were the basis for judging straightness. Helmholtz’s direction circles are not great circles, but rather circles that are parallel to great circles (like lines of latitude) that pass through a particular secondary position in the field of fixation as well as through what Helmholtz called the ‘occipital point’—a position directly opposite the primary position of the line of fixation.

Helmholtz was well aware that the optical centre of the human eye lies in front of the centre of rotation of the eyeball (1910, page 165) and that, as a consequence, the characteristics of images on the celestial sphere are not precisely the same as the characteristics of retinal images. For example, great circles on the celestial sphere do not project to great circles on the retinal surface, even if the eye were a perfect sphere. It may have been partly for this reason, as well as his more general empiricist philosophy of perception, that Helmholtz argued retinal local signs could not be innately ‘given’, as Hering had claimed, but instead had to calibrated. “How do we come to have this method of gauging the visual globe?” asked Helmholtz (1910, page 185).\(^2\) For Helmholtz, the method by which this calibration was achieved was through the eye movements needed to fixate different parts of the visual field: “We may possibly know from daily experience how the arm has to be reached forth in order to touch this object or that in order to hide it from the eye. And so such movements enable us to find out directly the direction of objects on the visual globe; and thus we learn to connect the special local signs of the sensation directly with the place in this field where the object belongs” (Helmholtz 1910, page 167).\(^3\) In other words, touch can educate vision (Gregory and Wallace 1963). Somewhat surprisingly, Helmholtz goes on to say: “This is likewise the explanation of how it is that we see objects erect, although their retinal images are upside down”.\(^4\) Would anyone nowadays argue that because our retinal images are inverted, there is a ‘problem’ for the visual system?

For Helmholtz, the celestial sphere can be thought of as a construct or framework for specifying the locations of objects in space in angular terms that is independent of

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\(^1\)“Ich ziehe es vor, in der folgenden Darstellung die beiden ausser unserem Auge liegenden Flächen an die Stelle der Netzhaut und des Netzhautbildes treten zu lassen, weil jene ein richtiger Ausdruck unseres thatsächlichen Bewußtseins sind, und weil bei der directen Eintragung aller Orte in die beiden Kugelfelder die Zweideutigkeit des Ausdrucks vermieden wird, die bisher so oft in die Irre geführt hat, als wüssten wir etwas von unserer Netzhaut, deren Größe und Ausdehnung, wenn gesagt wird, daß wir die lage der Objecte vor uns beurtheilen nach der Stelle der Netzhaut, welche getroffen wird” (Helmholtz 1867, page 539).

\(^2\)“wie kann eine solche Ausmessung des Sehfeldes entstehen?” (Helmholtz 1867, page 556).

\(^3\)“Wir können also direct durch solche Bewegungen die Richtung im Sehfelde ermitteln, wo sich die Objecte befinden, und wir lernen direct die besonderen Localzeichen der Empfindung zu verbinden mit dem Orte im Sehfelde, in den das Object gehört” (Helmholtz, 1867, p540).

\(^4\)“Dies ist auch der Grund, warum wir die Gegenstände trotz ihrer umgekehrten Netzhautbilder aufrecht sehen” (Helmholtz 1867, page 540).
the positions of the eyes. Note that the coordinate frame of Helmholtz's celestial sphere is fixed to the head, unlike Gibson's optic array that specifies the locations and movements of objects with respect to an abstract 'vantage point'. However, the optic array and celestial sphere are both defined in terms of spherical coordinates and both use the device of projecting or intercepting the visual rays onto a surrounding spherical surface.\(^{(5)}\) For Helmholtz, this was because we see the world as 'out there' and hence it is 'a more correct expression of our actual consciousness', whereas for Gibson the optic array was an attempt to get away from what he saw as the 'muddle' of retinal images. In fact, Helmholtz expressed similar misgivings about retinal images over a hundred years ago. He wrote: “The retinal images have nothing whatever to do with the localization of objects” (page 167).\(^{(6)}\) What did he mean by this statement? Presumably, Helmholtz was not denying that we need retinal images in order to see, but rather he appears to share Gibson's view that there are dangers in attaching too much importance to the particular characteristics of our retinal images. Helmholtz wrote “I myself am disposed to think that neither the size, form and position of the real retina nor the distortions of the image projected on it matter at all, as long as the image is sharply delineated all over ... In the natural consciousness of the spectator the retina has no existence whatever” (Helmholtz 1910, page 167).\(^{(7)}\)

Helmholtz may not have been correct in his explanation of how we judge the straightness of lines (Rogers and Brecher 2007) or why we don't see the world as upside-down, but he was surely right in stressing the advantages of describing and thinking about the visual world in terms of his celestial sphere, which, like Gibson's optic array, is uncontaminated by the distortions, imperfections, and philosophical confusions that belie our retinal images.

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\(^{(5)}\) It is important to emphasise that neither the use of spherical coordinates nor the projection of the array onto a spherical surface is in any sense crucial to an analysis of the available information because coordinates can always be remapped from one framework to another (Todd 1994; Howard and Rogers 1995). The utility of both conceptions is, in my view, much more in terms of being able to visualise the properties of the projected array.

\(^{(6)}\) “Die Netzhautbilder kommen bei der Localisation der Objecte eben gar nicht in Betracht” (Helmholtz, 1867, page 540).

\(^{(7)}\) “Auch halte ich für mein Thiel für wahrscheinlich, daß es ganz gleichgültig für das Sehen ist, welche Gestalt, Form, und Lage die wirkliche Netzhaut hat, welche Verzerrungen das Bild auf ihr erleidet, wenn es nur überall scharf ausgeprägt ist, und weder die Form der Netzhaut noch die des Bildes im Laufe der Zeit sich merklich verändert. Im natürlichen Bewußtsein des Schenden existiert die Netzhaut gar nicht” Helmholtz 1867, page 540.)
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