The art of binocular (a)symmetries

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Abstract
Visual experience of the world with two eyes reflects a balance between the symmetries and asymmetries of projections to them. Singleness of vision is served mainly by the stimulation of corresponding points on the two retinas whereas stereoscopic depth perception is based on non-correspondence or retinal disparities. Large disparities result in binocular rivalry. These distinctions are made pictorially by means of anaglyphs which need to be viewed with red/cyan filters in order to experience stereoscopic depth, binocular rivalry and their combination. Most pictures we view are flat and any apparent depth is alluded to by cues like perspective; they are best viewed with one eye. Binocular art, on the other hand, reveals to two eyes the consequences of asymmetries of stimulation that are not available to a single eye.

Keywords: monocular symmetry, binocular asymmetry, correspondence, disparity, stereoscopic depth, binocular rivalry, anaglyphs.

Introduction

In the context of binocular vision, symmetry and asymmetry operate in many ways. The eyes share the anatomical characteristics of many body parts in being bilaterally symmetrical. For an upright observer the eyes are separated laterally by about 6.4 cm. This, in turn, results in slightly different optical projections from objects to each eye. Despite this asymmetry, our experience of the three-dimensional world with both eyes open is of its singularity. Much of the history concerning vision with two eyes has centred on single vision. A solution proposed in the early 19th century was based on geometrical optics: if a circle is drawn through the centres of rotation of each eye and the point of binocular fixation then all points on the circumference of this circle will fall on corresponding points of each retina. This so-called binocular circle is shown in Figure 1 together with a portrait of Johannes Müller, who described it in 1838 [1]. It was considered that stimulation of corresponding points results in single vision and any points in space either outside or inside the circle would be seen double. That is, symmetry of stimulation was the basis of binocular single vision.

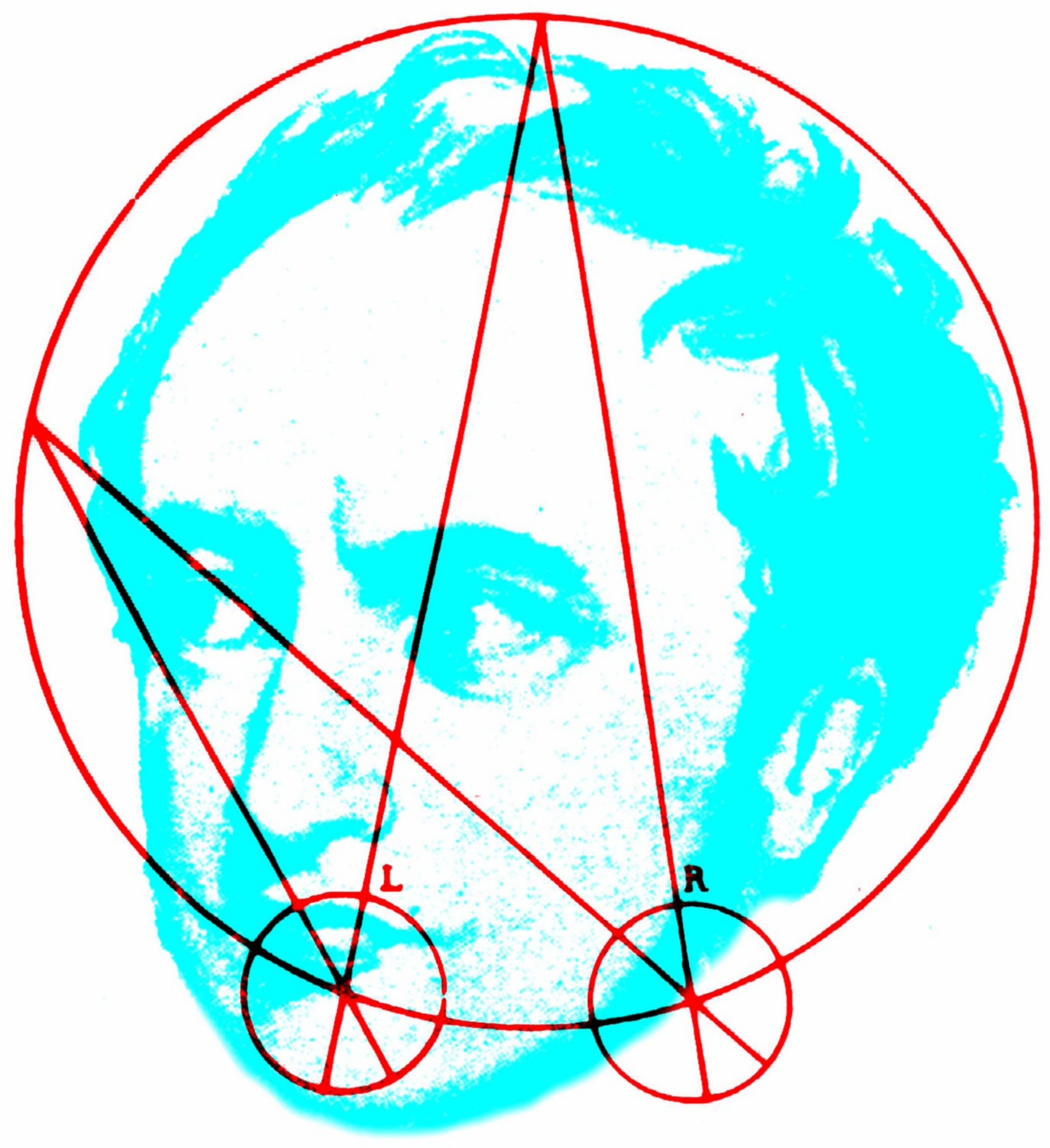


Figure 1. *Johannes Müller and his binocular circle* by Nicholas Wade. Müller linked the binocular circle with corresponding points on each retina.

The shortcomings of Müller's elegant theory were demonstrated in the same year with publication of an article [2] by Charles Wheatstone (Figure 2) describing his invention of the stereoscope and the experiments he conducted with it. Stimulation of slightly non-corresponding points resulted in not only single vision but also depth. Stereoscopic depth perception is based on binocular asymmetry. The battle between symmetry and asymmetry regarding stimulation of two eyes was waged throughout the following decades.

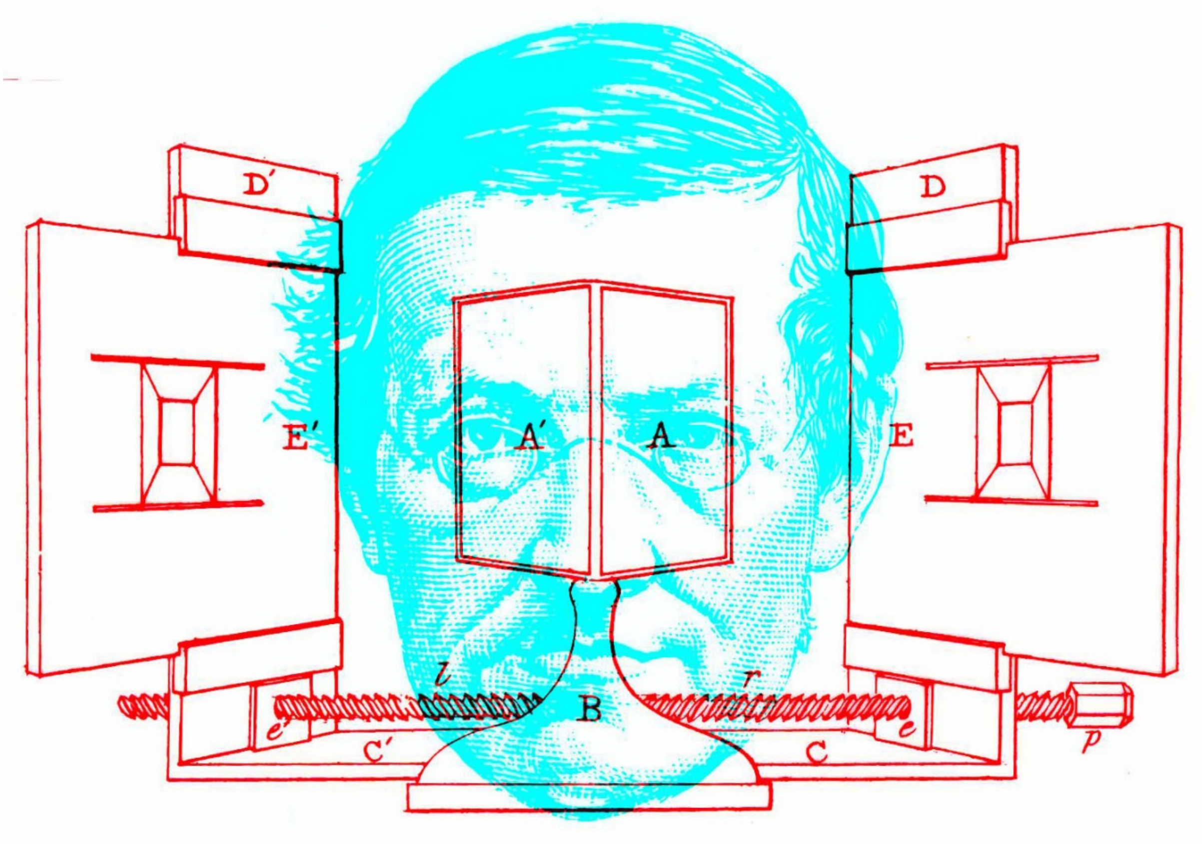


Figure 2. *Charles Wheatstone and his stereoscope* by Nicholas Wade. A portrait of Wheatstone together with a diagram of a mirror stereoscope from his original article [2]. The slightly different pictures of a truncated pyramid (E and E', neither of which are symmetrical) are reflected in the mirrors (A and A') to be seen separately by left and right eyes.

The first stereoscopes were based on mirrors, prisms or lenses but other systems for separating the images presented to each eye were later enlisted [3]. Anaglyphs are displays in which the left and right eye images are printed in different colours, such as red and cyan, and they are viewed through filters of the same colours. They have typically been used to present slightly different images to each eye so that they are seen in stereoscopic depth. The general standard is for red/left eye, cyan/right eye filters for viewing similarly coloured printed images. Anaglyphs can also be employed to present radically different images to each eye, as is the case for Figures 1 and 2: the portraits can be seen by one eye and the diagrams by the other. This results in binocular rivalry when viewed with both eyes through the red/cyan filters. Binocular rivalry represents asymmetry between the eyes rather than within patterns presented to them. There is also an asymmetry between the eyes in terms of their general function. It is referred to as eye dominance and it can be checked easily by reversing the filters in front of the eyes for the combination cyan/left eye, red/right eye.

Photography was announced to the public in 1839, the year after Wheatstone presented his stereoscope. Indeed, Wheatstone was aware of Talbot's experiments with paper negatives before they were made public. Wheatstone asked Talbot to take stereoscopic photographs for him, but Talbot made the separations between the two views too large to be combined stereoscopically, resulting in rivalry.

Stereoscopic vision

Wheatstone's invention of the stereoscope transformed both the vision of pictures and the picture of vision. That is, it ushered in a fashion for stereoscopic photography as well as reshaping scientific theories of spatial vision. Stereoscopes enable presentation of different pictures to each eye; if the differences are small, depth can be seen, but if they are large then the two pictures engage in rivalry. Two-dimensional representational art works allude to depth that they do not contain; they are essentially monocular. The distinction between monocular and binocular art is that monocular pictures reveal to one eye what is concealed from two (stereoscopic depth), whereas binocular pictures reveal to two eyes what is concealed from one (depth and rivalry).

Stereoscopes opened up a new world of art. Stereoscopic pictures could supply a dimension missing from those that preceded them – depth. The new art presented graphical difficulties for artists but these were overcome by the novel processes of photography. As Wheatstone astutely observed: "What the hand of the artist was unable to accomplish, the chemical action of light, directed by the camera, has enabled us to effect" [4]. The science of stereoscopy was advanced when computer-generated random dot displays were developed in the 1960s so that depth perception could be investigated independently of object recognition. With a wider variety of patterns for carrying disparities the binocular pictures have an appeal of their own. Photographs of natural shapes like leaves, flowers, branches and stones can be manipulated graphically to create complex patterns of symmetry; disparities can be introduced in these that cannot be detected until combined with similar patterns to yield stereoscopic depth.

Conventional photographs, like that in Figure 3a, contain perspectival clues to the relative separations between different structures which can be amplified stereoscopically (Figure 3b). Wheatstone [2] recognised this, which is why he used outline drawings for most of his illustrations. When the left and right eye patterns are reversed when viewing stereoscopic photographs, thereby reversing the disparities, the apparent depth is not reversed. This can easily be seen by reversing the filters in front of the eyes (cyan/left eye, red/right eye): monocular perspective is more powerful than stereopsis when they are in competition.

a b

Figure 3. *The Blyth Fountain, Newport on Tay* by Nicholas Wade. Left, a conventional photograph and right, a stereoscopic anaglyph of the same scene. The apparent depth is alluded to in **a** but it is also amplified by the binocular disparities in **b**.

Wheatstone wished to produce pictures in which disparity alone was in operation, devoid of painterly cues. He could not fulfil his desire but it was achieved over a century later by Béla Julesz [5] with his computer-generated random-dot stereograms; they enabled stereoscopic depth perception to be investigated independently of monocular object recognition. Those devised by Julesz are pairs of matrices of squares in which the contents of each cell are randomly assigned as black or white; displacing a region in one display and combining them in a stereoscope results in that region appearing in depth. A variation on that theme is shown in Figure 4. The pattern of random dots looks flat and square through the red filter alone as it does through the cyan filter, but with both eyes it is transformed: a central square is seen in depth beyond the surrounding surface the right side of which itself slowly slants away. The square appears more distant than the background in what is referred to as uncrossed disparity. What was smooth and symmetrical with one eye is seen as a square in depth on a surface receding on the right hand side with two. With longer viewing the apparently more distant right side looks larger than the left so that a symmetrical outer square seen with one eye becomes a trapezoid with two. Moreover, reversing the eye/filter combination reverses the depths so that the square appears nearer (crossed disparity) than the slanted background, the right side of which appears smaller than the left. The central square also looks smaller when it is apparently nearer. The symmetry seen with one eye alone becomes doubly asymmetrical with two eyes. The depth asymmetry can be induced over the whole surface (as with the slant) or in an enclosed part of it (as with the central square).

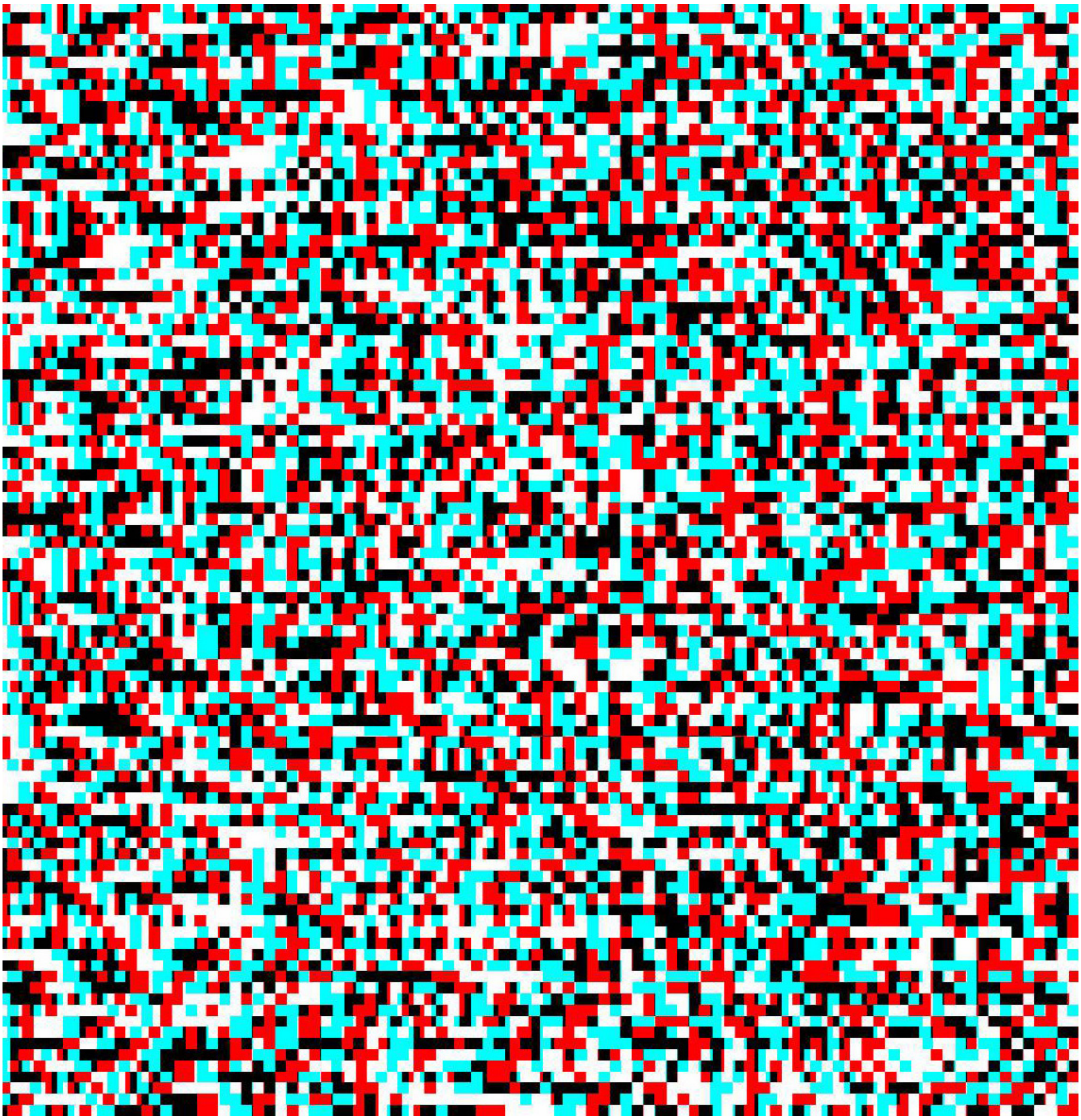


Figure 4. *Square in depth on a slanted surface* by Nicholas Wade.

Random dot displays can carry displaced patterns because the elements (black or white squares) are regular but lacking binocular symmetry so that the displacement cannot be detected by a single eye. The square elements are the same size in an ordered array. More complex patterns than random dots can be used to express binocular asymmetries as long as the elements are small; unlike random dot patterns, the sizes of the elements vary and they are not arranged in an orderly array. Many patterns in our environment have these characteristics and can be used as carrier patterns for stereoscopic displays. An example, shown in Figure 5, is derived from a photograph of gravel stones – the individual stones are about the same size but their distribution is not regular. Displacements of the stones in one pattern will not be detected but when combined with a similar pattern without displacements in the other eye, depth can be seen, the sign (nearer or farther) of which is dependent on the arrangement of filters.

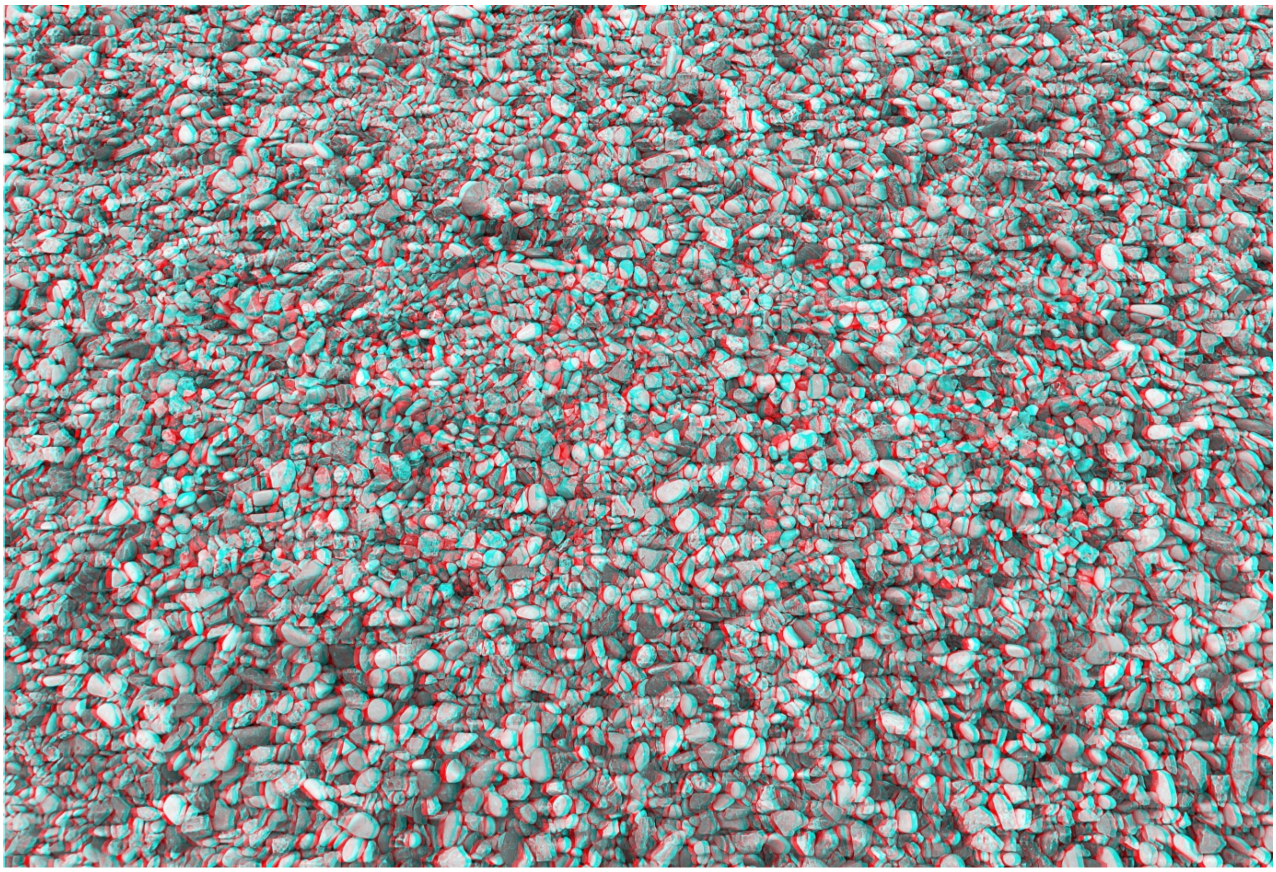


Figure 5. *DEPTH in gravel stones* by Nicholas Wade.

Plant patterns are well-suited to act as carriers for stereoscopic displays and multiple depth planes can be represented by varying the sizes and disparities of the asymmetrical components in anaglyphs, as in Figure 6. The elements in depth are themselves leaf-shaped and they are stacked to look like a pile or a hole of leaves, depending upon the filters/eye combination.

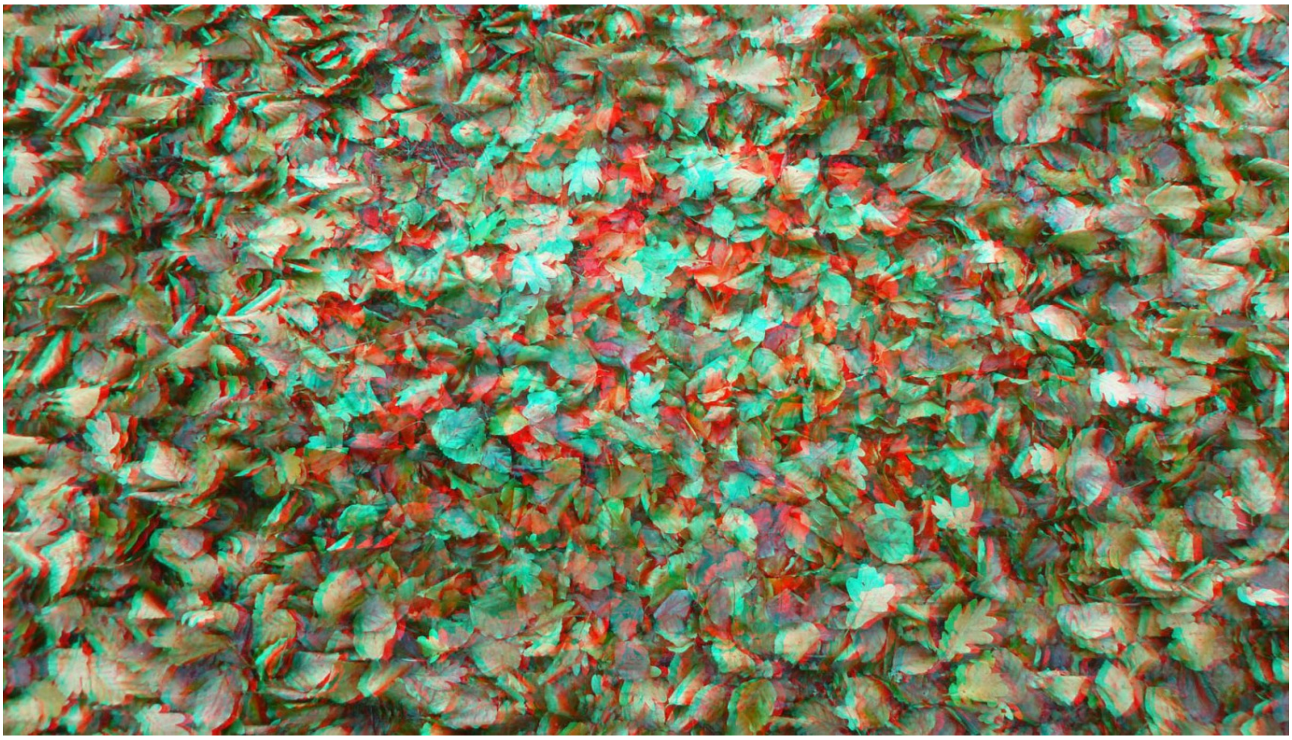


Figure 6. *Leaf structures* by Nicholas Wade. The initial impression is of a large leaf shape in depth which articulates over time to be seen in several depth planes.

The carriers for binocular asymmetries can also be graphics derived from photographs of naturally occurring patterns. The carrier pattern in Figure 7 is derived from a photograph of snow-covered tree branches which was graphically manipulated to create a design with vertical and horizontal symmetries. The design that can be seen in depth with red/cyan glasses is itself symmetrical about a vertical axis; it is also ambiguous. Either two facing profiles can be seen or a central vase. The vase/face design is a traditional two-dimensional figure/ground ambiguity which switches from one to the other interpretation with prolonged viewing. The ambiguity is reduced or removed with anaglyphic viewing: the component that appears closer is seen as figure against the background. This can easily be seen by reversing the eye/filter arrangement.

Figure 7. *Vase/faces ambiguity in depth* by Nicholas Wade.

The binocular asymmetries involved in stereoscopic depth perception are small relative to those that can occur with binocular rivalry stimuli. Indeed it is often the intention to make the rivalling stimuli as different as possible in order to enhance competition between them.

Binocular rivalry

Art involving binocular rivalry has been neglected relative to that based on stereoscopic depth perception, but it exposes more compelling aspects of binocular asymmetry. Thus, binocular art is broader than stereopsis because it can address the competition between the eyes in rivalry as well as their cooperation in yielding stereoscopic depth. A simple combination of contours that will be seen in rivalry when viewed through the filters is shown in Figure 8. The letters of the word are easy to read but the patterns within them engage in binocular rivalry when viewed through the red/cyan filters. The instability in the appearance of the patterns is complex and does not reflect a simple switching between the eyes but a complex mosaic of eye and pattern dominance. That is, rivalry reveals competition between the eyes as well as the pattern elements. There is no 'standard' arrangement for the eye/filter combination for rivalry patterns and reversing them is recommended.

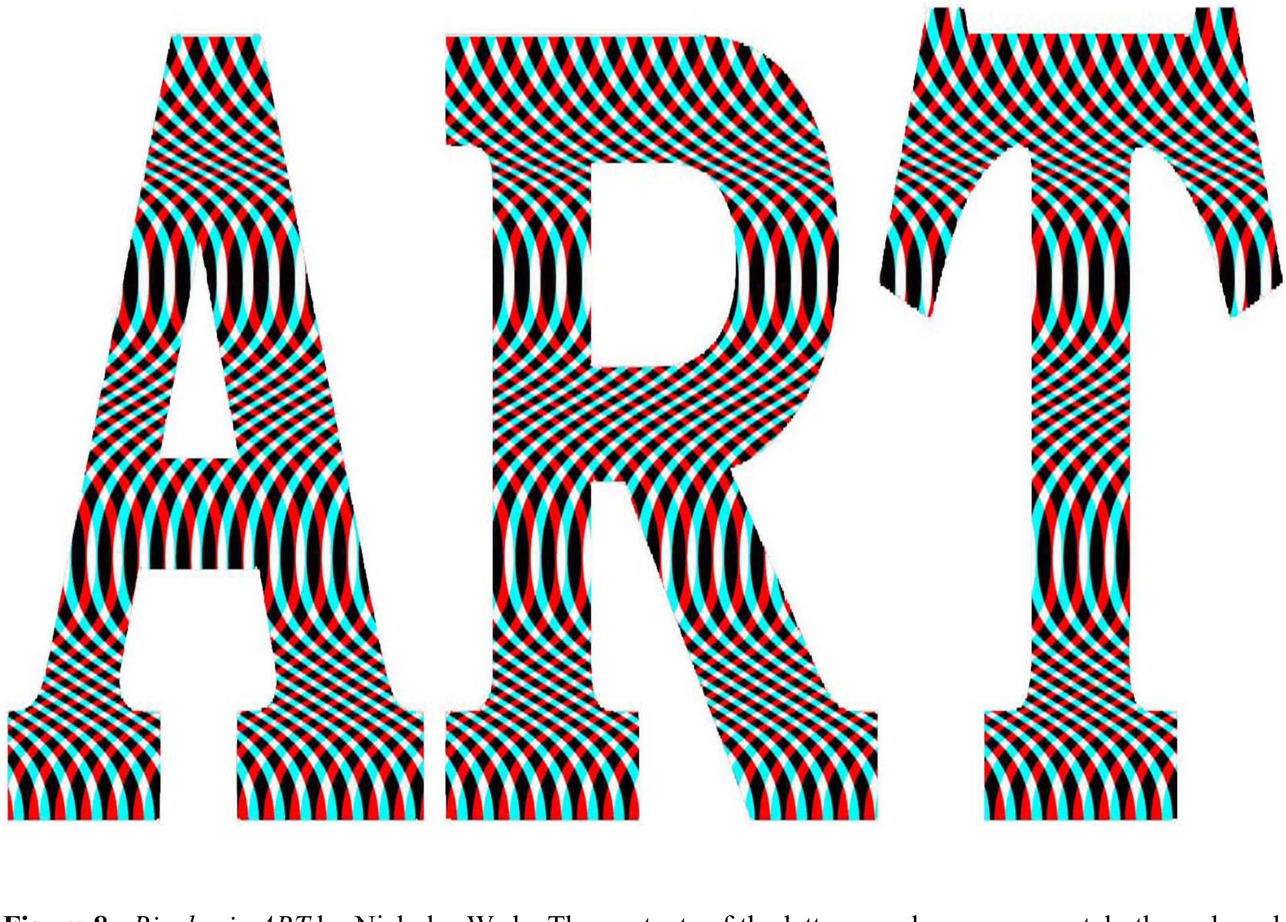


Figure 8. *Rivalry in ART* by Nicholas Wade. The contents of the letters can be seen separately through each colour filter; they are symmetrical patterns of curves the directions of which are reversed for each eye. With binocular viewing through the filters the patterns will be unstable and dynamic over time. The differences perceived when the filters are reversed will reveal which eye is dominant.

Rivalling patterns can be graphics (like Figure 8), photographs (Figure 9) or combinations of the two (Figure 10). Many more examples can be found in Wade [3, 6].

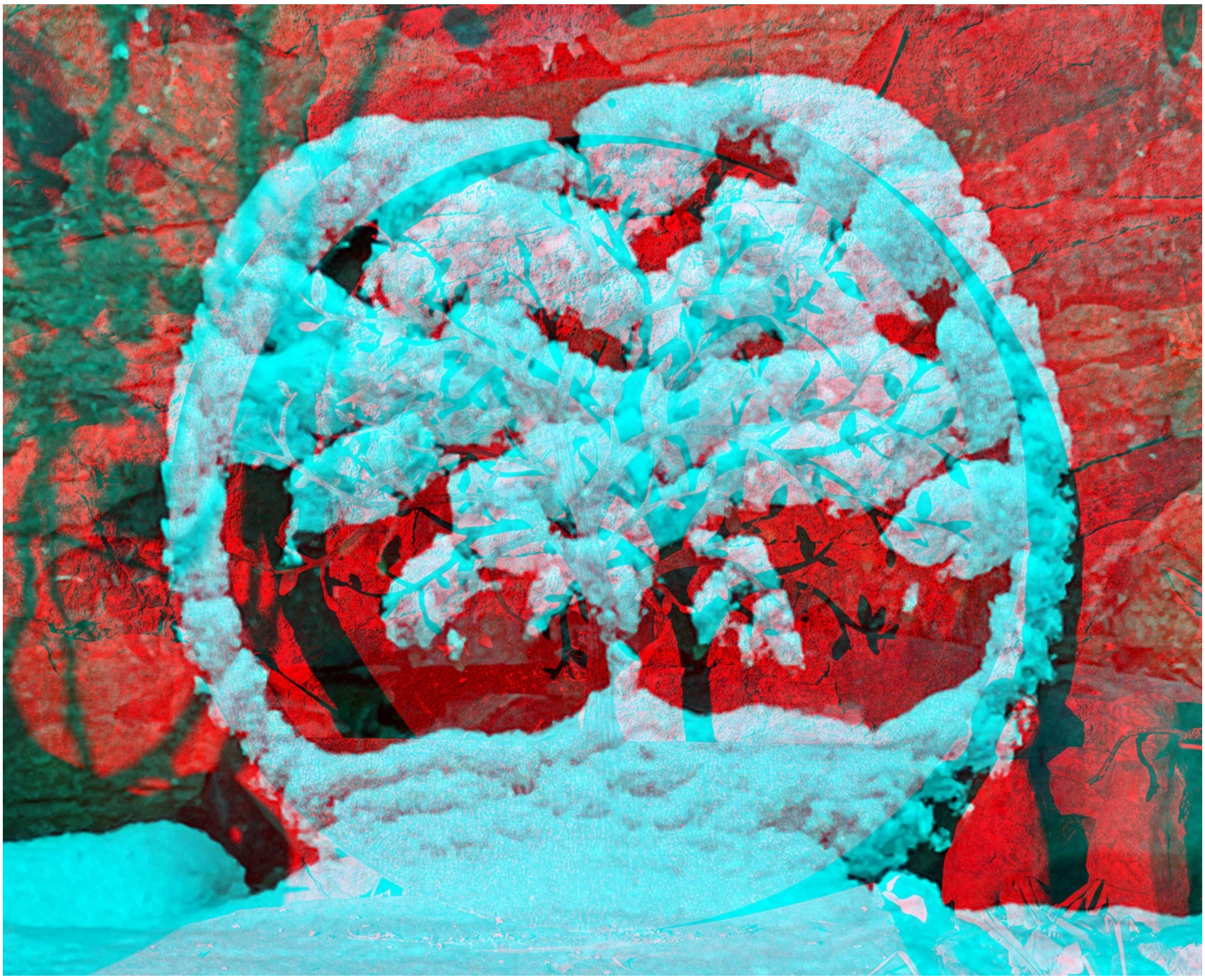


Figure 9. *Summer/Winter* by Nicholas Wade. The same structure (an ornamental metal tree) was photographed in summer and winter and combined so that one eye sees the sunlit tree and its shadows whereas in the other photograph it is snow-covered.

Combining photographs with graphic designs offers the opportunity of finding some relationship between the components. In the case of Figure 10, two symmetrical structures are binocularly interwoven. A photograph of the City Hall, Toronto can be seen in one eye and a graphic design of the CN Tower, which dominates the city, in the other. The CN Tower is embedded in a moiré pattern alluding to its function as a communication tower and it is position between the curved structures of the City Hall.

Figure 10. *Toronto and the CN Tower* by Nicholas Wade. The curved buildings of Toronto City Hall, enclosing the domed City Chambers, can be seen through the cyan filter. The structure of the CN Tower can be discerned in the waves emanating from it when viewed through the red filter. With both eyes the two landmarks of Toronto vie for visual dominance.

Rivalry and stereopsis

Both stereoscopic depth perception and binocular rivalry are robust phenomena but can they co-exist at the same time in the same place? Scientists have examined this in some detail because of its theoretical significance. While it is evident that rivalry and depth can be experienced in the same stimulus pair at different locations the evidence is less clear that they can be experienced simultaneously at the same location. The following images show that they can. For example, in Figure 11 the rivalry in the outer annulus of the image below is restricted to corresponding regions of each eye whereas that in the central disc is seen both in rivalry and depth. The rivalry remains when the filters are reversed as does the depth, but its sign changes.

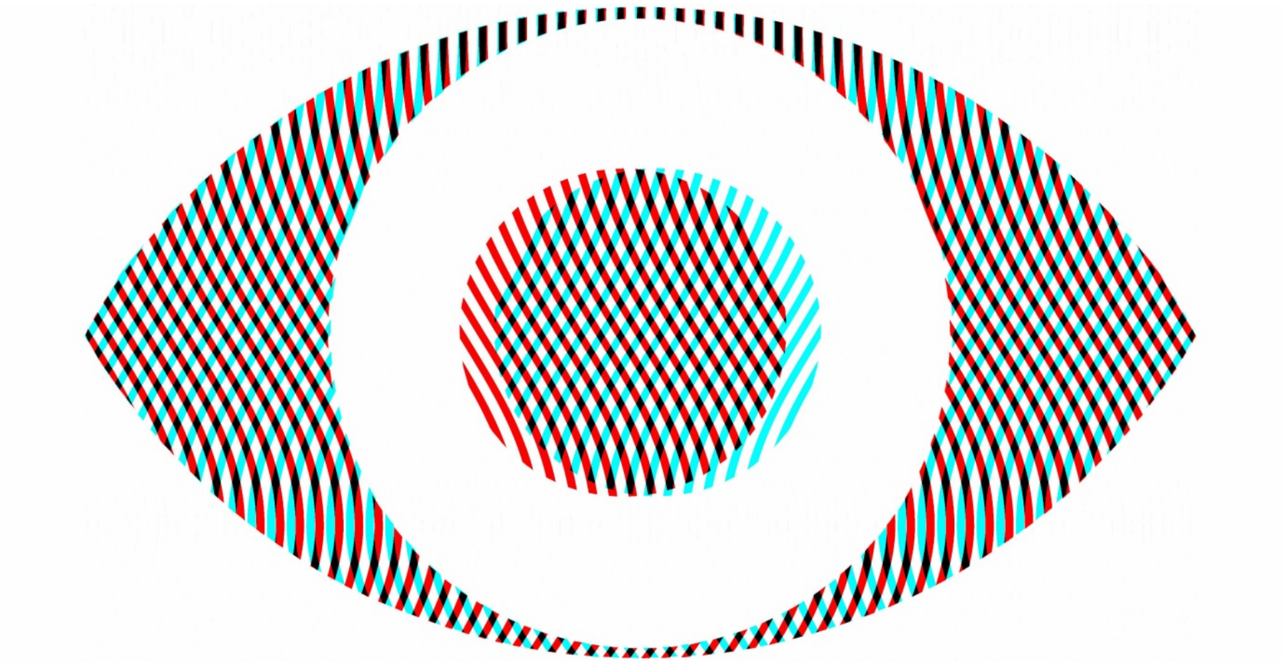


Figure 11. *Reyevalry in depth* by Nicholas Wade. The contours defining the symbolic eye are in rivalry but the central circle is also in disparity; despite this, it appears in a different depth plane to the outer area.

The rivalling patterns can also carry portraits, not in the simple manner shown in Figures 1 and 2 but more subtly embedded in one of the component patterns. Moreover, stereoscopic depth can be added to the combination. Portraits that rival with one another can be of the same person either in contrasting postures, at different ages or carried by appropriate graphical or textual motifs. The two components need not be of the same person so that a wide variety of possibilities can be entertained [3].

In Figure 12, the portrait is of Bela Julesz who introduced computer-generated random-dot stereograms and has made many intriguing stereograms based on them [7]. The portrait is embedded in a natural texture and presented to a single eye. A similar pattern is seen by the other eye but there is a displacement within it. When viewed with two eyes through the red/cyan filters the portrait is fleetingly visible within a circular surround which is in constant stereoscopic depth.

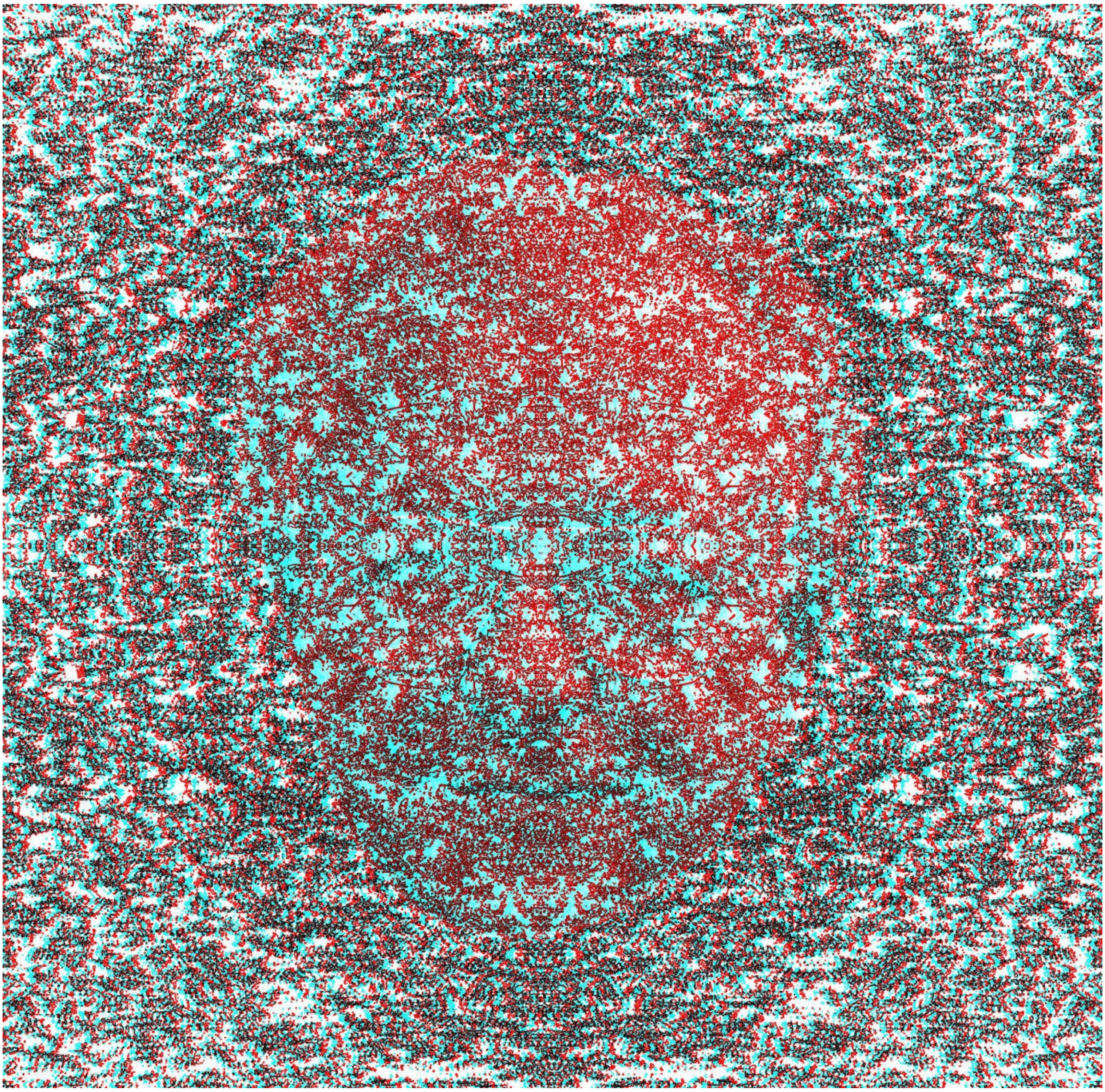
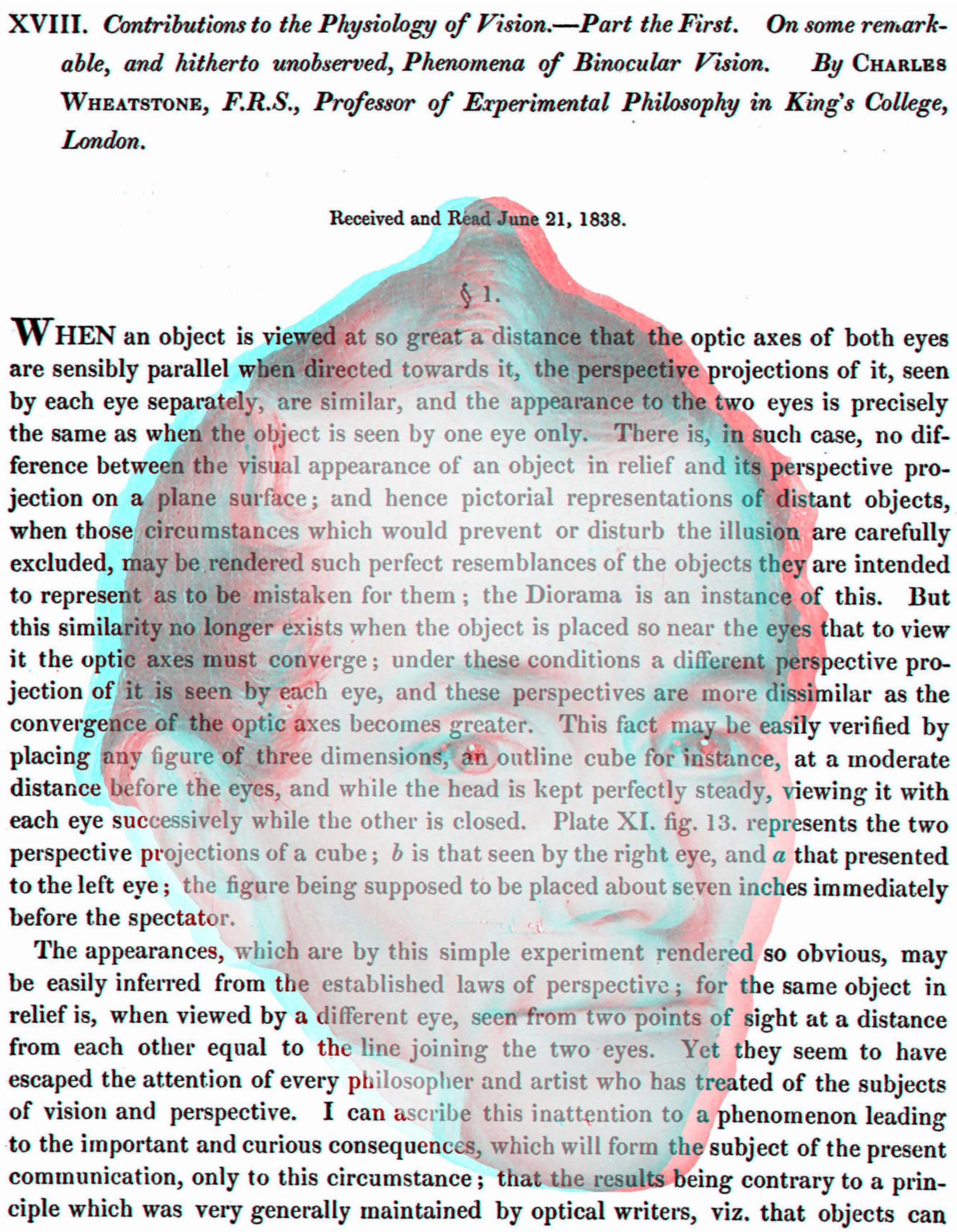


Figure 12. *Bela Julesz in rivalry and depth* by Nicholas Wade. The portrait of Julesz can be seen through the red filter, embedded in the pattern derived from a photograph of a bush which is seen through the cyan filter. With both eyes a stereoscopic circle remains visible while the portrait is sporadically seen.

Conclusion

What we see with two eyes is a result of a balance between symmetry and asymmetry, between order and disorder. That the world is seen as single despite our eyes receiving two slightly different views of it is largely a consequence symmetry – the stimulation of corresponding points in the two eyes. That it is seen in depth is due to asymmetries of stimulation – non-corresponding or disparate points define the relative separations between objects, as long as the disparities are not too large. Gross asymmetries of stimulation result in binocular rivalry in which all or parts of the pattern presented to one eye are in a state of dominance or suppression with respect to the corresponding regions in the other. Moreover, these states are transient so that the patterns perceived are continually changing. An additional aspect of binocular asymmetry is eye dominance. The two eyes often differ in their acuities, their motilities and their powers of suppression.

It is fitting that the final image (Figure 13, overleaf) pays homage to the pioneer of stereoscopy, Charles Wheatstone, who invented the instrument that made the experimental study of binocular vision possible and demonstrated that asymmetries of stimulation define stereoscopic depth. It also displays binocular asymmetry in a subtle way. Wheatstone's seemingly transparent portrait can be seen in depth relative to the text surrounding it and the sign of depth will reverse with reversal of the colour filters. That is, the portrait appears either nearer or farther than the text, which is itself not stereoscopic. It looks as if the transparent features of the face are seen behind the text or they hover in front of it. The effects might take some seconds for the depths of the portrait to articulate in this way. The distant face occurs with the red/left eye and cyan/right eye arrangement, and the hovering face with the reverse. The text is the opening page of Wheatstone's [2] paper to the Royal Society describing his invention of the stereoscope and the experiments he conducted with it. The date on which it was delivered, June 21, is now celebrated as International Stereoscopy Day.



XVIII. *Contributions to the Physiology of Vision.—Part the First. On some remarkable, and hitherto unobserved, Phenomena of Binocular Vision.* By Charles Wheatstone, *F.R.S., Professor of Experimental Philosophy in King's College, London.*

Received and Read June 21, 1838.

§ 1.

When an object is viewed at so great a distance that the optic axes of both eyes are sensibly parallel when directed towards it, the perspective projections of it, seen by each eye separately, are similar, and the appearance to the two eyes is precisely the same as when the object is seen by one eye only. There is, in such case, no difference between the visual appearance of an object in relief and its perspective projection on a plane surface; and hence pictorial representations of distant objects, when those circumstances which would prevent or disturb the illusion are carefully excluded, may be rendered such perfect resemblances of the objects they are intended to represent as to be mistaken for them; the Diorama is an instance of this. But this similarity no longer exists when the object is placed so near the eyes that to view it the optic axes must converge; under these conditions a different perspective projection of it is seen by each eye, and these perspectives are more dissimilar as the convergence of the optic axes becomes greater. This fact may be easily verified by placing any figure of three dimensions, an outline cube for instance, at a moderate distance before the eyes, and while the head is kept perfectly steady, viewing it with each eye successively while the other is closed. Plate XI. fig. 13. represents the two perspective projections of a cube; *b* is that seen by the right eye, and *a* that presented to the left eye; the figure being supposed to be placed about seven inches immediately before the spectator.

The appearances, which are by this simple experiment rendered so obvious, may be easily inferred from the established laws of perspective; for the same object in relief is, when viewed by a different eye, seen from two points of sight at a distance from each other equal to the line joining the two eyes. Yet they seem to have escaped the attention of every philosopher and artist who has treated of the subjects of vision and perspective. I can ascribe this inattention to a phenomenon leading to the important and curious consequences, which will form the subject of the present communication, only to this circumstance; that the results being contrary to a principle which was very generally maintained by optical writers, viz. that objects can

Figure 13. *Wheatstone and his announcement of the stereoscope* by Nicholas Wade.
The monocular images each contain the same partially transparent portrait of Wheatstone so that the text continues through it. The location of the portrait with respect to the text is shifted laterally so that when the text is aligned the portrait displays disparities. This can be seen by viewing the two monocular images separately. When viewed with the red/cyan filters in front of the eyes the partially transparent portrait appears either closer than the text or more distant.

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