SEEING WITH TWO EYES AND HEARING WITH TWO EARS

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Abstract

Immersion in a three-dimensional world of sight and sound is the natural state of perception. It is dependent upon differential spatial patterns received by two eyes and upon time and intensity differences to two ears. However, these have not been the aspects of seeing and hearing that have received the attention of students of the senses in the past. The experiences of a single visual world and the singleness of sound perception have masked attention to differences in the stimuli available to two eyes and two ears and to the ways in which they are processed. Phenomena involving seeing with two eyes have been commented upon for millennia whereas those about hearing with two ears are much more recent. One of the principal phenomena that led to studies of binaural hearing was binocular colour mixing. Direction and distance in visual localization were analyzed before those for auditory localization, partly due to difficulties in controlling the stimuli. Experimental investigations began in the 19th century with the invention of instruments like the stereoscope and pseudoscope, soon to be followed by their binaural equivalents, the stethophone and pseudophone.

Keywords: binocular, binaural, dichoptic, dichotic, stereoscope, stethophone, pseudoscope, pseudophone

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Introduction

Stereo immersion in seeing and hearing is the normal condition of perception: objects are seen in depth and sounds are heard in space but these have not been the historical issues addressed. The unity of perceptual experience has masked attention to differences in the stimuli available to two eyes and two ears and to the ways in which they are processed. Contemporary approaches to stereo immersion are concerned with how the natural binocular and binaural processes can be simulated or extended beyond the natural ranges. Accordingly, stereoscopic seeing and stereophonic hearing often present the perceiver with stimulation that exceeds what would be naturally available. It is of interest to examine the ways in which binocular vision and binaural hearing have been investigated in the past and this needs to be placed in the context of the wider studies of vision and hearing.

Understanding how the eyes work together provided the impetus for examining integration of signals from the ears. The advantages of having two eyes were recorded long before those for two ears were appreciated. This is reflected in the experimental studies that were undertaken to examine seeing and hearing, not to mention the contrivances that were invented to stimulate two eyes or two ears. The historical research on binocular vision has been enormous, but the same does not seem to apply to binaural hearing. In part, this reflects the marked differences in how we can compare perception with one or two organs. It is easy to close one eye and examine monocular vision but it is very difficult to 'close' one ear and study monaural hearing. Moreover, we can move our eyes either in the same direction (version) or in opposite directions (vergence) but humans have no equivalent means of moving the ears independently or in unison.

The divergent histories of seeing with two eyes and hearing with two ears is reflected in the times at which terminologies associated with them were introduced. This in turn relates to the instruments that were devised to stimulate the paired organs. Porta (1593) used the term 'binis oculis' (two eyes) in Book 6 of his *De Refractione* and Schyrleus de Rheita (1645) referred to a 'binoculum telescopium' (binocular telescope). By contrast a 'bin-aural stethoscope' was not introduced until much later by Alison (1861) and experiments on 'binaural audition' were not undertaken until the 1870s. Charles Wheatstone named the instrument of his invention a "Stereoscope, to indicate its property of representing solid figures" (Wheatstone, 1838, p. 374). Thereafter a distinction could be made between 'binocular' which involved stimulating two eyes with equivalent patterns and 'stereoscopic' for the visual perception of depth based on retinal disparities. It was a similar concern with the 'solidity' of auditory space that led Alexander Graham Bell to refer to "the stereophonic phenomena of binaural audition" (Bell, 1880, p. 169). Techniques for presenting different stimuli to each of the paired organs opened new experimental avenues in their study. With the recognition that two ears do work together, a new terminology for stimulating the ears differentially emerged (Wade & Ono, 2005). They were given the labels 'dichoptic' for binocular vision and 'dichotic' for binaural hearing. The term 'dichotic' was coined by Stumpf (1916); it referred to the stimulation of each ear with a different sound. It was distinguished from the simultaneous stimulation of each ear with the same sound. The application of dichoptic to the stereoscopic or haploscopic stimulation of the eyes followed the adoption of 'dichotic' in studies of binaural hearing.

Two eyes

In his article describing the stereoscope, Wheatstone (1838) noted that "No question relating to vision has been so much debated as the cause of the single appearance of objects seen by both eyes" (p. 387). Binocular single vision has been a source of experimental interest for over two thousand years (Howard & Rogers, 2012) but the same does not apply to binaural single audition – if the term itself has been used. Double vision can readily be observed by gently pressing one eye, it is an early factor in strabismus, and it has frequently been experienced as a consequence of drunkenness. Moreover, double vision can be induced experimentally, by presenting different stimuli to each eye. Many means of achieving this were available before the invention of the stereoscope (see Wade, 1987; Wade & Ngo, 2013; Wade & Ono, 2012). For example, a range of methods was applied to the study of binocular vision in the 18th century, many of which had been introduced earlier still.

The essence of investigating binocular vision was distilled from the methods adopted for stimulating the two eyes. Ptolemy, in the second century, appreciated that monocular and binocular visual directions were not necessarily the same (Howard & Wade, 1996; Smith, 1996). In order to confirm this empirically, he constructed a board on which he could place vertical rods at different distances in the midline of the eyes (Figure 1). There followed a description of one of the most commonly used examples of crossed and uncrossed visual directions: with fixation on the far rod, the nearer one appeared double, and to the left with the right eye and to the right with the left eye; the reverse occurred with fixation on the nearer rod. Essentially the same demonstration is now more frequently made with two fingers, rather than rods, held at different distances from the eyes in the median plane of the head. Ptolemy stated that singleness of vision with two eyes occurred when the two visual directions corresponded, thus introducing the concept of correspondence into binocular vision. He modified his board to take three rods and found that objects appeared single to two eyes when they were in the same plane as the fixation point. These facts were interpreted in terms of the visual axes and the common axis. A similar board was constructed by Alhazen in the 11th century, and he placed wax cylinders of different colours on it (Figure 1).

Another method of stimulating two eyes is shown in Figure 2; it is an illustration by Rubens printed in a book on optics by Aguilonius (1613). The cosmic observer fixates on the central cross (on the screen), thus producing crossed visible directions of the near object. The putti are pointing to the discs on the screen which mark the locations of the crossed directions. Rubens' engraving demonstrated the technique of fixating on one object located further from the eyes than another (see Ziggelaar, 1983). Aguilonius also introduced the terms 'horopter' and 'stereographic'. The horopter was the plane in which, with central fixation, peripheral objects appeared single with two eyes. Stereographic projection involved representing on a flat plane three dimensional objects (like a sphere).

Aristotle considered that both eyes were moved from a single source, and he also stated that vision with one eye was superior to that with two. Euclid's analysis of binocular vision, as of spatial vision generally, was geometrical; he examined three dimensions of a sphere that could be observed by two eyes, and simply related them to the amount of the spheres that would be seen. Euclid's use of a sphere was to have unexpected implications because Leonardo da Vinci examined binocular projections to the eye from a sphere (Figure 3). Leonardo struggled long and hard with the contrast between monocular and binocular vision (Wade, Ono & Lillakas, 2001). He was able to utilize the concept of Alberti's window which provided a monocular match between a picture and a view of a scene from a single point. But what happens when two viewpoints are adopted? Leonardo examined this many times in the context of a small object lying in front of a background. He returned to the issue repeatedly as indicated by the many diagrams he made of it. In each instance, vision with two eyes was optically and phenomenally different from that with one. The example he used, of viewing a sphere with a diameter less than the distance separating the eyes, reflected one condition Euclid analysed, but Leonardo added the characteristic of seeing the whole background. As Wheatstone (1838) remarked: "Had Leonardo da Vinci taken, instead of a sphere, a less simple figure for the purpose of his illustration, a cube for instance, he would not only have observed that the object obscured from each eye a different part of the more distant field of view, but the fact would also perhaps have forced itself upon his attention, that this object itself presented a different appearance to each eye. He failed to do this, and no subsequent writer within my knowledge has supplied the omission" (p. 372).

Leonardo made many similar drawings illustrating the superiority of binocular over monocular vision all involving spheres. The distinction was amplified by the comparison between a representation of a scene and its perception: "A Painting, though conducted with the greatest Art and finished to the last Perfection, both with regard to its Contours, its Lights, its Shadows and its Colours, can never show a *Relievo* equal to that of Natural Objects, unless these be view'd at a Distance and with a single Eye" (Leonardo, 1721, p.178). Porta (1593) also considered vision with two eyes but came to a radically different conclusion to Leonardo. Porta maintained that we see with only one eye at once and he provided evidence for this from binocular rivalry.

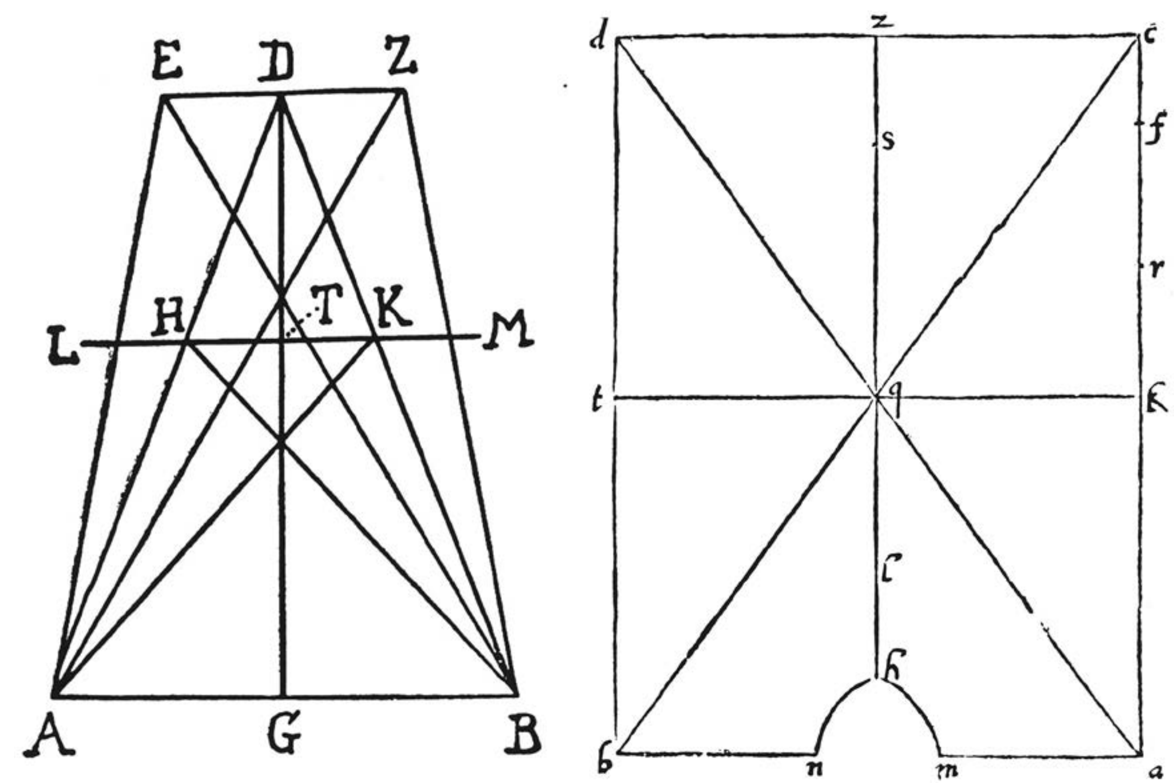

Figure 1. Binocular boards used by Ptolemy (left) and Alhazen (right).

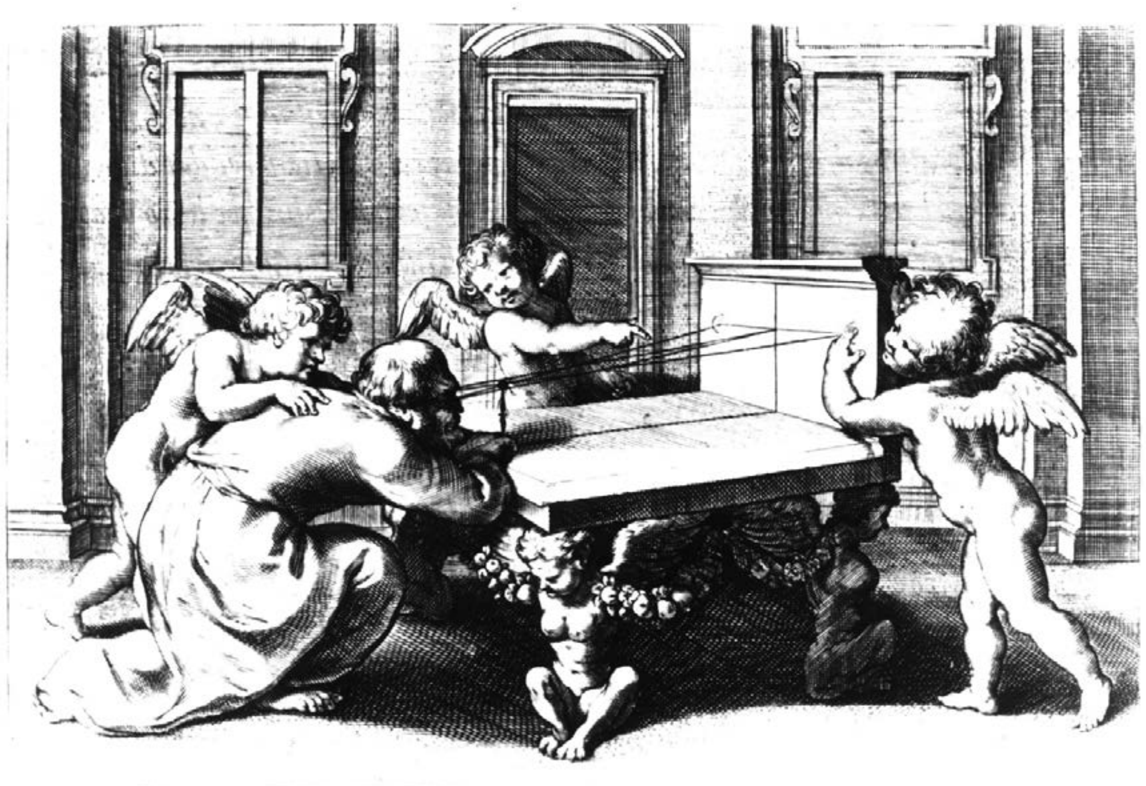

Figure 2. Crossed visible directions: with fixation on the cross (on the screen) the near object produces crossed visible directions as marked by the discs on the screen, to which one of the putti is pointing (Aguilonius, 1613, frontispiece to Book IV).

Viewing different pages of a book with different eyes resulted in reading one alone. This lead to interest in eye dominance and Porta (1593) introduced tests for both sighting and rivalry dominance, which were assigned to the right side. He wrote: "Nature has given us two eyes, one on the right and the other on the left, so that if we are to see something on the right we use the right eye, and on the left the left eye. It follows that we always see with one eye, even if we think both are open and that we see with both" (p.143). Despite having equated the optics of the eye with that of a *camera obscura*, Porta's dioptric diagrams (Figure 3) were neither consistent nor accurate.

In the 18th century the most widely studied aspect of binocular vision was how different colours presented to different eyes were seen. Many novel methods of presenting the colours to separate eyes were devised. Desaguliers (1716) placed an aperture in such a position that two more distant, adjacent objects were in the optical axes of each eye. He showed that dichoptically presented coloured lights rival rather than combine. That is, no colour combination took place dichoptically, and the colour rivalry was more evident with intense stimuli. Du Tour (1760) also provided a clear description of binocular colour rivalry. He achieved dichoptic combination by another means: he placed a board between his eyes and attached blue and yellow fabric in equivalent positions on each side, or the fabric was placed in front of the fixation point. When he converged his eyes to look at them they did not mix but alternated in colour. Yet another technique was to view different coloured objects through two long tubes, one in each optic axis. This method was used by Reid (1764), and he saw the colours combined although his

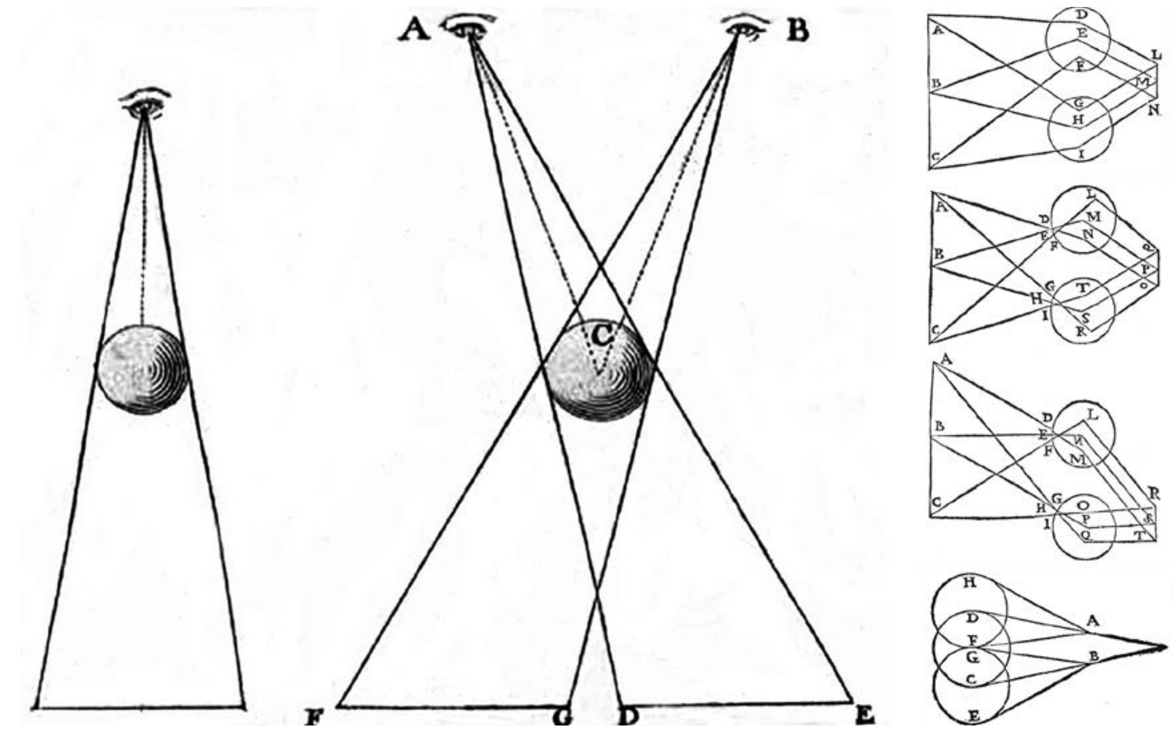

Figure 3. Left and centre, Leonardo's diagrams of monocular and binocular observation of a sphere the diameter of which is smaller than the separation between the eyes (from Du Fresne, 1651). Right, Porta's (1593) diagrams of binocular combination.

description was not without its ambiguity: the colours were not only said to be combined, but also one "spread over the other, without hiding it" (p. 326). Similar effects were observed by Wells (1792) who found that: "in all my experiments upon this subject I have remarked, that, when the two objects appeared united, each was seen, notwithstanding, in its proper colour; the red, for example, appearing as it were through a transparent green, and the green, in the same experiment, as through a transparent red" (p. 46). Venturi (1802) placed blue and yellow papers next to one another on a table and over-converged his eyes to combine them: "I have repeated this experiment often and with care, and I have never experienced a third colour from the two overlapping colours" (p. 389). This was taken to be evidence that the nerves from the two eyes did not combine in the brain. These observations led both Wells and Venturi to examine binaural hearing.

Dichoptic colour combination could be examined with greater ease after the stereoscope had been invented: different coloured patches could be placed on the separate arms of the stereoscope so that the ensuing experience could be reported. Wheatstone (1838) found that blue and yellow discs engaged in rivalry rather than combination. After over one hundred fifty years of research it is evident that whether mixture or rivalry occurs depends on many factors such as luminance, saturation, stimulus duration and colour difference.

A wide variety of binocular instruments had been devised before the stereoscope was invented. Binocular versions of telescopes and microscopes were available in the 17th century, but they did not add to the understanding of binocular vision (Wade, 1987). The stereoscope was invented in the early 1830s, and it opened a new world for the study of binocular vision. That world was the laboratory, and with the aid of the stereoscope the methods of physics could be applied to the investigation of spatial vision. Wheatstone made mirror and prism stereoscopes as early as 1832, but he only described the mirror version in his classic memoir of 1838 (Figure 4). Wheatstone described the mirror stereoscope at a meeting of the Royal Society of London in June, 1838 and he demonstrated the device to a meeting of the British Association for the Advancement of Science held at Newcastle in August, 1838. Wheatstone invented the stereoscope to establish the nature of binocular depth perception. With the aid of the instrument he was able to manipulate the pictures presented to each eye and to observe the depth that was produced. In so doing, he found that:

> …the projection of two obviously dissimilar pictures on the two retinæ when a single object is viewed, while the optic axes converge, must therefore be regarded as a new fact in the theory of vision. It being thus established that the mind perceives an object of three dimensions by means of the two dissimilar pictures projected by it on the two retinæ, the following question occurs: What would be the visual effect of simultaneously presenting to each eye, instead of the object itself, its projection on a plane surface as it appears to that eye (Wheatstone, 1838, pp. 372373).

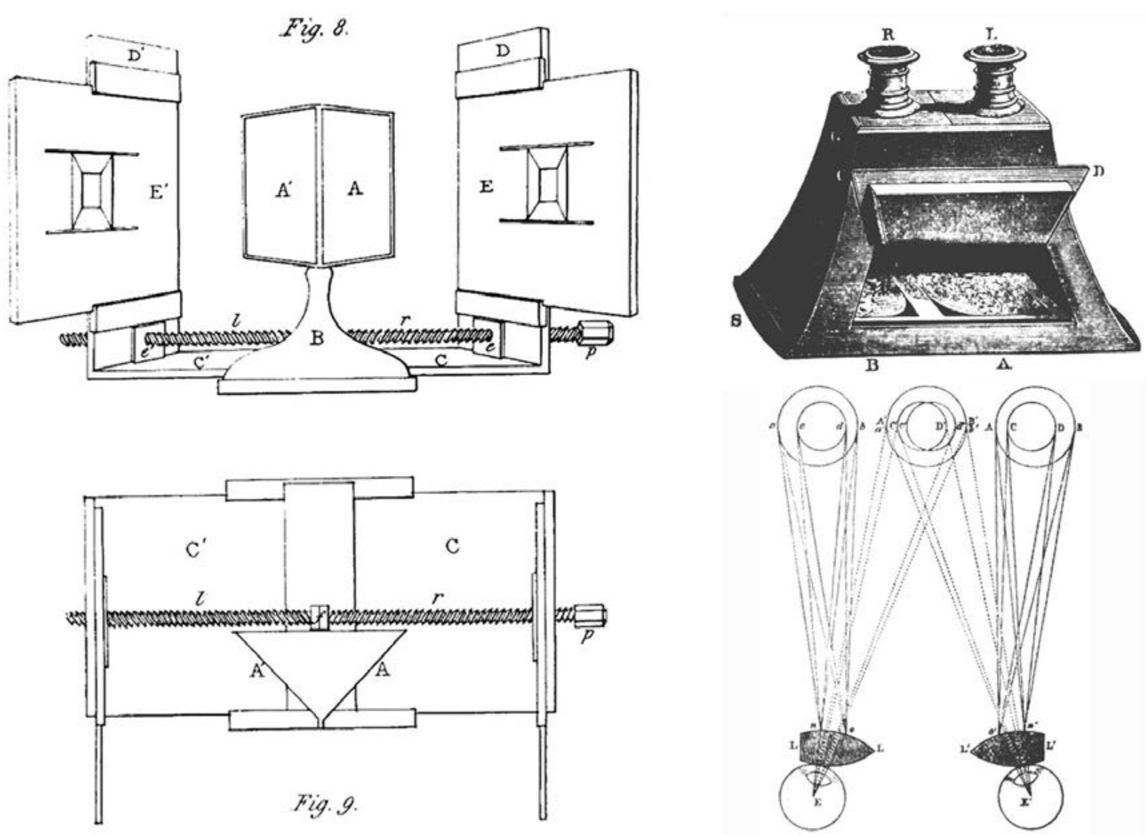

Figure 4. Left, Charles Wheatstone's mirror stereoscope viewed from the front and above (from Wheatstone, 1838). Right, Brewster's lenticular stereoscope (from Brewster, 1856).

Prior to the invention of the stereoscope, the issue of single and double vision was the primary focus. Both Vieth (1818) and Müæller(1826) concluded on geometrical grounds that a stimulus on the circumference of a circle that passes through the two eyes and the intersection of the two visual axes leads to single vision. The geometry of retinal disparities was well known but such disparities were considered to lead to double vision rather than depth perception. The stereoscope transformed the understanding of binocular vision and it spawned a variety of alternative ways of presenting different pictures to the eyes. The most popular model of stereoscope was Brewster's (1849b) lenticular version (Figure 4). It consisted of a single lens cut in half so that the two half-lenses, when appropriately mounted, acted as magnifiers as well as prisms, fusing adjacent stereo drawings or photographs. The first model was made by George Lowdon, an optical instrument maker in Dundee, but the version displayed at the Great Exhibition, held in Crystal Palace, London in 1851 was made by Louis Jules Duboscq of Paris. It was more popular than the mirror stereoscope because it was more compact and could be used more conveniently with paired photographs. Brewster (1849a) also described a binocular camera and later illustrated a wide variety of methods for combining stereo-pairs (Brewster, 1851), as did Dove (1851).

Wheatstone's (1852) second article on binocular vision was published fourteen years later. He described and illustrated an adjustable mirror stereoscope, a prism stereoscope, and a pseudoscope for reversing disparities. The main purpose of these was to extend the range of conditions under which the two eyes could be stimulated. Wheatstone (1852) used the stereoscope with adjustable arms to vary the four circumstances mentioned in the quotation (retinal size, convergence, accommodation, and disparity). He applied the pseudoscope to reverse the normal relations between monocular and stereoscopic cues to depth: "With the pseudoscope we have a glance, as it were, into another visible world, in which external objects and our internal perceptions have no longer their habitual relation with each other" (p. 12). He remarked on the difficulty of perceiving reversals of relief with the pseudoscope, and the illuminating conditions that are necessary for such reversal.

Both Wheatstone and Brewster were acquaintances of William Henry Fox Talbot, who made public his negative-positive photographic process in the year after Wheatstone's first article on the stereoscope appeared (Schaaf, 1992). He immediately grasped the significance of photographing scenes from two positions, so that they would be seen in depth when mounted in the stereoscope. In 1840, he enlisted Talbot's assistance to take stereo-photographs for him; when they were sent to him the angular separation of the camera positions used to capture the two views was too large (47.5 deg) and Wheatstone suggested that 25 deg would be more appropriate. Klooswijk (1991) has reprinted a section of Wheatstone's letter to Talbot, and has himself taken stereo-photographs of the bust Talbot probably employed from camera angles of 47.5, 25.0, and 1.75 deg. However, it was Brewster's lenticular stereoscope which benefited from the invention of photography, and the stereophotographs that exist of Wheatstone and Brewster were made for the lenticular stereoscope.

Helmholtz was greatly influenced by Wheatstone and his stereoscope and he described a telestereoscope which exaggerated disparities and the depth perceived (Helmholtz, 1857). He used stereoscopic phenomena to advance his empiricist approach to perception: "*The sensations of the senses are tokens for our consciousness, it being left to our intelligence to learn how to comprehend their meaning*" (1925, p. 533). This was contrasted to the nativism of Hering (1862) and the battleground was binocular vision. Helmholtz concluded "The invention of the stereoscope by Wheatstone made the difficulties and imperfections of the Innate Theory of sight much more obvious than before" (Helmholtz, 1873, p. 274). Hering presented an interpretation of depth perception based on innate local signs and his conflicts with Helmholtz have been well documented by Turner (1994).

Wheatstone was well aware of the fact that object recognition could influence the depth perceived but he did not have any means of removing objects from the stereopairs. With the advent of computer generated images, Julesz (1971) realised Wheatstone's dream – he made random dots stereograms in which there was nothing presented to either eye alone that could indicate the depth to be seen. Only with their combination could the depth emerge in what he called cyclopean vision.

A binocular depth phenomenon described before Wheatstone invented his stereoscope can be seen in patterns that consisted of horizontal repetitions, like the flowers on wallpaper. It was with such a pattern, illustrated by Brewster (1844), that gave the phenomenon its name – the wallpaper illusion. With fixation on the same element with both eyes the pattern appears to lie in the plane of the page. However, by combining adjacent identical images and maintain them (with the same convergence of the eyes) the pattern appears to hover above the page or be seen through it. The depth at which the pattern is seen corresponds to the plane at which the eyes converge: the farther apart the combined elements are the greater the apparent depth (see Wade, 2016). If slight variations in the locations of the repetitions along rows are introduced then more complex depth planes are visible and aspects of disparity processing become involved. The surface no longer looks flat but stepped in wedges from top to bottom. Wallpaper illusions can be seen without the aid of any viewing devise as they only involve converging the eyes to combine neighbouring elements. More systematic manipulations of repetitions and disparities were devised by Tyler and Clarke (1979) to create what they have called autostereograms. In the 1990s algorithms for generating autostereograms with computers made them enormously popular. In large part this was because a viewing device was not necessary in order to experience the stereo effects, although some people do find it difficult to converge their eyes appropriately and to maintain that degree of convergence.

The anaglyph method, enabling overprinted red and blue images to be combined through similarly coloured filters was introduced at about the same time by Rollmann (1853). A mechanical precursor of modern electronic shuttering systems was developed by Claudet (1865). Descriptions of more recent stereoscopic techniques can be found in Blundell (2011). Portraits of the pioneers of binocular vision are shown in Figure 5.

Two ears

The history of research on hearing with two ears is both shorter and more recent than that for seeing with two eyes. The instruments invented for examining binaural hearing were generally based on earlier ones for binocular stimulation. Again, Wheatstone's experiments on binaural hearing provided a stimulus for much that was to follow, and he probably made the first binaural instrument. The studies on hearing with two ears prior to Wheatstone were based largely on analogies with binocular colour mixing. In his book on refraction, Porta (1593) speculated about ear dominance as he had about eye dominance: "If we hear someone talking with the right ear we cannot listen to another with the left ear; and if we wish to hear both we shall hear neither, or indeed if we hear something with the right we lose the same amount from the left" (p. 143). Porta's ideas were not pursued by others and it is for these reasons that McManus (2002) noted: "In contrast to the neglect of ear dominance, eye dominance has been much more thoroughly studied" (p. 153).

It was in the context of dichoptic colour mixing that Wells (1792) suggested a thought experiment to link binaural hearing with binocular vision:

> From the fact of the two colours being thus perceived distinct from each other, I would infer, by analogy, a mode of argument indeed often fallacious, that if it were possible for us to hear any one sound with one ear only, and another sound with the other ear only, such sounds would in no case coalesce either wholly or in part, as two sounds frequently do, when heard at the same time by one ear; that consequently, if the sounds of one musical instrument were to be heard by one ear only, and those of another, by the other ear only, we could have little or no perception of harmony from such sounds; and that, if any succession of sounds emitted by one instrument, we were to hear the 1st, 3d, 5th , and so on, by one ear only, and the 2d, 4th, 6th, and so on, by the other ear only, we should be deprived, in a considerable degree, of the melody of such sounds, as this seems to depend in a great measure upon a new impression being made upon the auditory nerve by one sound, before the impression of the sound immediately preceding has passed away. (Wells, 1792, p. 46)

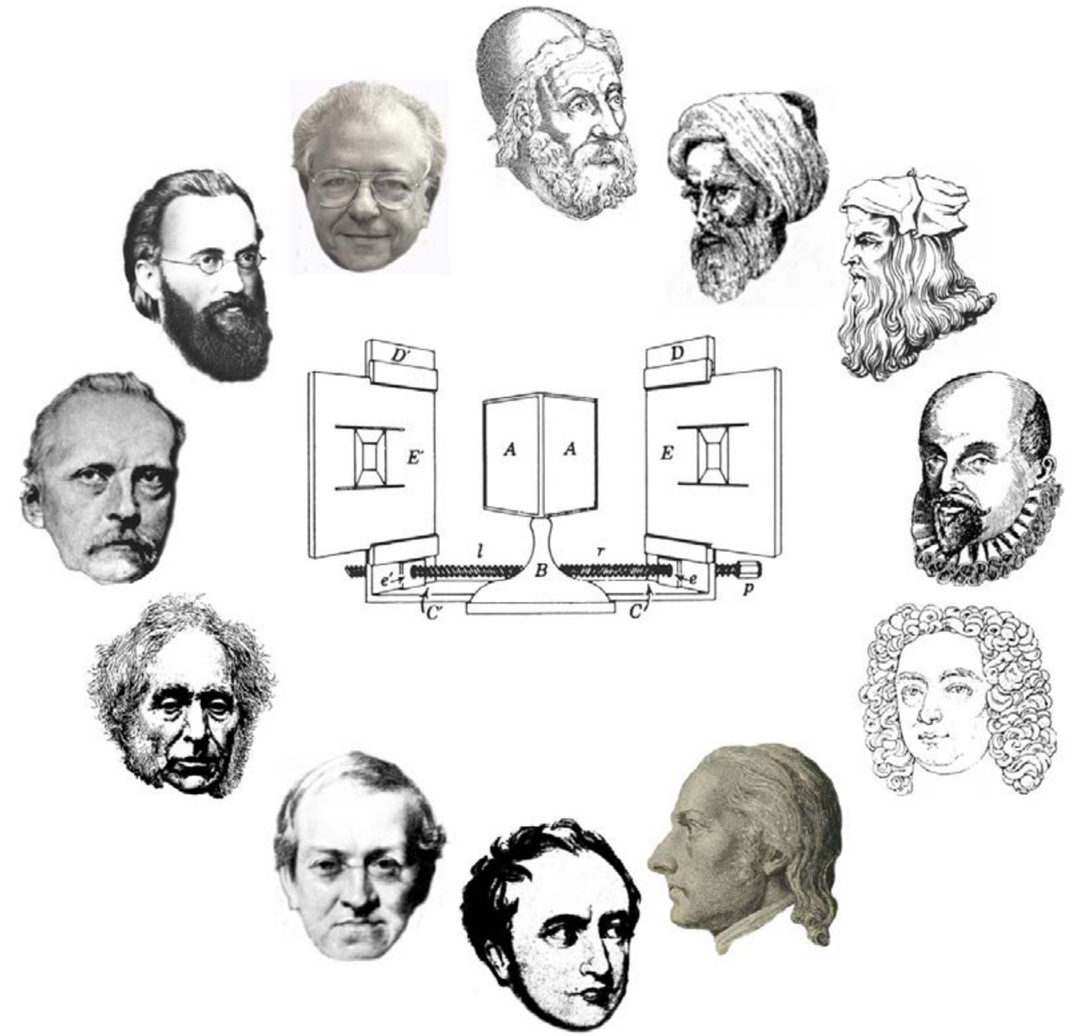

Figure 5. *Pioneers of binocular vision* by Nicholas Wade. Wheatstone's mirror stereoscope is surrounded by (clockwise from the top in chronological sequence): Ptolemy, Alhazen, Leonardo da Vinci, Giovanni Battista della Porta, Jean Théophile Desaguliers, Gerhard Vieth, Johannes Peter Müller, Charles Wheatstone, David Brewster, Hermann Helmholtz, Ewald Hering, and Bela Julesz.

> This probably constitutes one of the earliest considerations of examining dichotic listening experimentally, although Wells did not conduct such an experiment. Thus, the stimulus for examining dichotic listening derived from studies of dichoptic colour perception and the same reasoning was applied by Venturi (1802).

Studies of auditory localization are considered to have commenced with Venturi's experiments comparing listening with both ears or with one blocked by a finger. A blindfolded listener stood on a flat and unbounded surface and notes from a flute were played from various directions at a distance of 40–50 meters. In his first study one ear was stopped by a finger. Sounds could be located when they were perpendicular to the open ear. This direction was called the auditory axis, following the concept of the visual axis. His second study was also with one ear stopped but the blindfolded listener turned until the sound was loudest. This occurred when the sound was in the auditory axis of the open ear. The third study was with both ears open and a stationary head. The listener was able to determine with reasonable accuracy the direction of a sound, but this could not be maintained when one ear was stopped with a finger. Partially blocking one ear changed the apparent direction of the sound. On the basis of this observation Venturi (1802) stated: "Therefore the inequality of the two impressions, which are perceived at the same time by both ears, determines the correct direction of the sound" (p. 186). Venturi also established that a listener with both ears open could not distinguish between a sound directly in front of them or behind. Neither Wells nor Venturi devised instruments specifically for investigating binaural hearing but this was to change when Wheatstone approached the topic.

The Wheatstone family business was concerned with the manufacture of musical instruments (see Bowers, 2001 for a biography of Wheatstone). Wheatstone was led to the study of vision through the visual expression of acoustic phenomena. Indeed, his first scientific paper was on acoustical figures (Wheatstone, 1823), and he later expressed these with a philosophical toy of his invention, which he called the kaleidophone or phonic kaleidoscope (Wheatstone, 1827a). It enabled an observer to see the paths of rapidly vibrating rods (see Wade, 2002, 2004). Wheatstone wrote: "In the property of 'creating beautiful forms,' the Kaleidophone resembles the celebrated invention of Dr. Brewster" (1827a, p. 344). The kaleidophone was an extension of a method described by Young (1800), in which silvered wire was attached to a piano string so that its vibration could be observed with the aid of a magnifying glass. Wheatstone constructed the kaleidophone to amplify the vibrations so that they could be seen by the naked eye. Silvered glass beads were attached to the ends of rods having different cross-sections and shapes; when the rods were bowed or struck complex figures could be seen in the light paths traced by reflections from the beads.

Wheatstone's early experiments were addressed to Chladni figures and a range of other auditory phenomena (Wheatstone, 1823, 1827b, 1833). The initial instrument involved wires connected to metal plates that could be placed over each ear which he called a 'microphone'. That is, the first microphone was binaural (Figure 6). Wheatstone did describe some experiments he conducted with this binaural device. He also reported that the normal combination of two different sounds to yield a third sound did not occur if the two sounds were presented separately to the two ears:

> Select two tuning-forks the sounds of which differ by any consonant interval excepting the octave: place the broad sides of their branches, while in vibration, close to one ear, in such a manner that they shall nearly touch at the acoustic axis; the resulting grave harmonic will then be strongly audible, combined with the two other sounds; place afterwards one fork to each ear, and the consonance will be heard much richer in volume, but no audible indications whatever of the third sound will be perceived. (Wheatstone, 1827b, p. 71)

Wheatstone's description accords well with the prediction Wells (1792) made on the basis of his thought experiment of presenting different sounds to each ear. It is noteworthy that Wheatstone was one of the few writers on binocular vision who cited Wells's theory of binocular visual direction. The simple experiments with the binaural microphone might have sharpened Wheatstone's awareness of combining signals from paired sense organs. His chance observations that led to the invention of the stereoscope occurred only a few years later (Wade, 2002).

The auditory equivalent of the stereoscope was invented by Alison (1859) and it was called a stethophone (Figure 6). It consisted of independent ear tubes so that different sounds could be listened to. He was not stimulated to study binaural hearing on the basis of Wheatstone's stereoscope, but as a consequence of his experiments in audition. Alison's experiments mostly involved two watches and he formulated two laws: "1st, that sounds of the same character are restricted to that ear into which they are conveyed in greater intensity, and 2nd, that sounds differing in character may be heard at the same time in the two ears respectively, even if they be made to reach the ears in different degrees of intensity" (1859, p. 205). Alison (1861) later referred to the stethophone as the bin-aural stethoscope. He was among the first to use the term 'binaural audition' and it was adopted by Thompson (1877) and Steinhauser (1877, 1879) in their investigations.

It was Wheatstone's pseudoscope that provided the incentive for Thompson (1879) to make a pseudophone (Figure 6) for

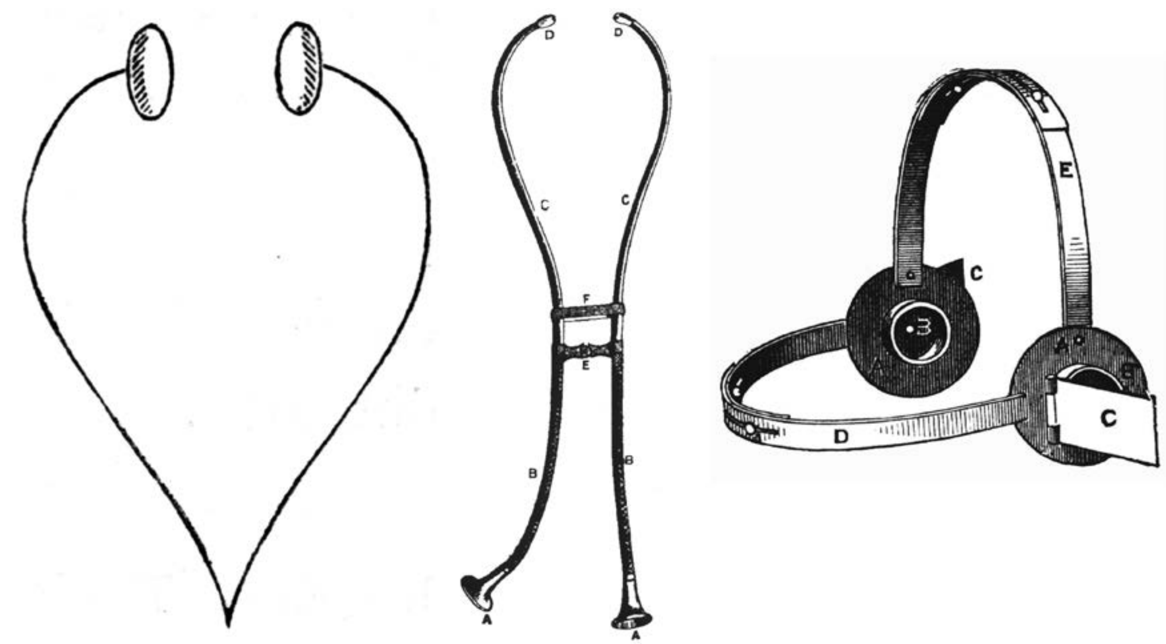

Figure 6. Left, Wheatstone's microphone, centre, Alison's stethophone and right, Thompson's pseudophone, all as illustrated in their original articles. Wheatstone wrote: "The greater intensity with which sound is transmitted by solid rods, at the same time that its diffusion is prevented, affords a ready means … of constructing an instrument which, from its rendering audible the weakest sounds, may with propriety be named a Microphone" (1827b, p. 69). Alison described the stethophone thus: "The tubes are composed of two parts nearly equal in length, one near the ear-knob, made of metal (C); while the other part, near the collecting cup, is made of metal wire (B), to impart flexibility. The ear-end is curved, so as to approach the ear, and is supplied with an ivory knob (D) for insertion into the meatus externus. The other end of the tube, being intended to collect sound, is supplied with a hollow cup, or receiver (A) made of wood, or some such material" (1859, pp.197-198). Thompson described the pseudophone in the following way: "The simple instrument for which the author suggests the name Pseudophone consists of a pair of ear-pieces, A A, furnished with adjustable metallic flaps or reflectors of sound, C C, which can be fitted to the ears by proper straps, D and E, and can be set at any desired angle with respect to the axis of the ears, and can also be turned upon a revolving collar about that axis so as to reflect sounds into the ears from any desired direction" (1879, p. 387).

hearing: "The Pseudophone is an instrument for investigating the laws of Binaural Audition by means of the illusions it produces in the acoustic perception of space. It is therefore the analogue for the ears of the Pseudoscope of Wheatstone, which serves to illustrate the laws of Binocular Vision by means of the illusions it produces in the optical projections" (Thompson, 1879, p. 385).

Soon after Wheatstone's invention of the stereoscope, it enjoyed a commercial success as a 'philosophical toy' (Wade, 2002, 2004). This was not only because of the instrument itself, but also its combination with paired photographs; the wonders of the world could then be seen in depth and in the comfort of the Victorian parlor (see Pellerin & May, 2014). A similar success occurred later with stereophonic sound. Recording the sound with two or more microphones and reproducing it with two or more loudspeakers was found to provide realistic reproduction and now the "stereo" is a standard part of any auditory entertainment system and of our language.

Binocular colour combination also led Dove (1841) to compare vision and hearing with paired organs. He demonstrated that stereopairs were seen in depth even when illuminated by an electric spark, thereby excluding the occurrence of eye movements during observation. Dove sounded different tuning forks to each ear and noted that they combined, unlike the case with dichoptic colour mixing. The opposite outcome was reported by Seebeck (1846), who used sirens as well as tuning forks. He found that binaural sounds as well as binocular colours combined. Weber (1846) was similarly stimulated to examine an

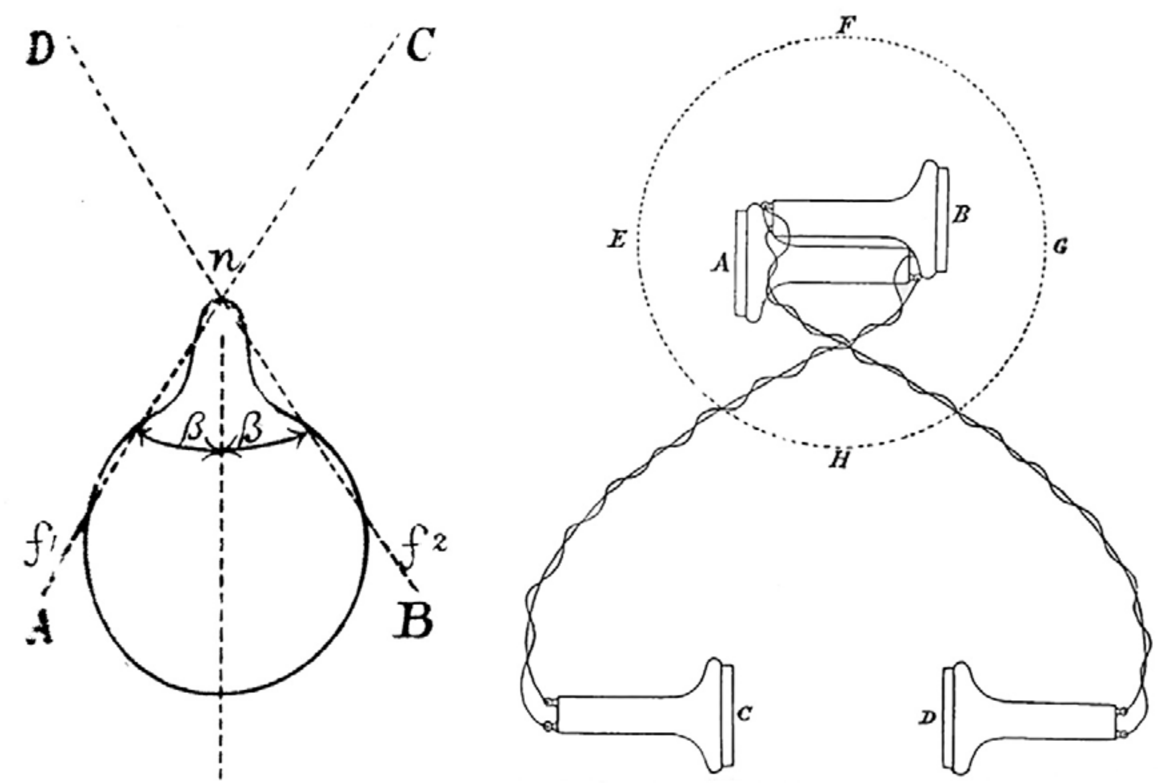

Figure 7. Left, a diagram from Steinhauser (1879) showing the head from above and the limits of direct and mixed binaural audition. Right, the arrangement of telephones in the studies described by Bell (1880).

aspect of binaural hearing on the basis of his belief that two different binocular stimuli could not be perceived simultaneously. He carried out the following observation:

> If I take two watches, whose ticking differs slightly in rate, and hold them near one ear so that the sound is only heard *via* that ear and not by the other, then I can distinguish those times at which the ticks of one watch fall in between the ticks of the other: I can perceive them as a repeated rhythm. But if I hold one watch next to each ear, while indeed I can perceive that one ticks faster than the other, I cannot perceive this repeated rhythm, and the ticking of the two watches therefore gives quite a different impression from that in the first instance. (Ross & Murray, 1978, p. 147)

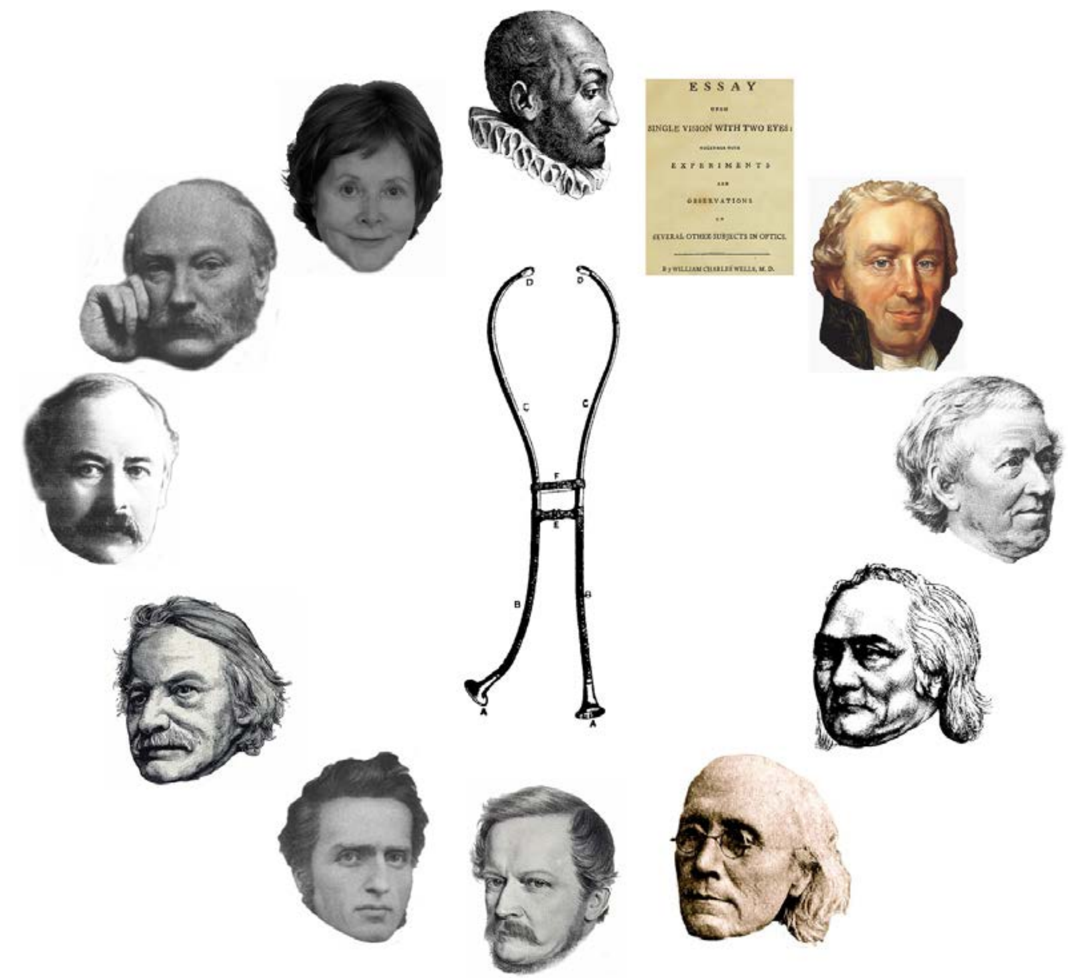

Figure 8. *Pioneers of binaural hearing* by Nicholas Wade. Alison's stethophone is surrounded by portraits of those who have advanced knowledge of binaural perception. Wells is represented by the title page of his book as I have not been able to find a portrait of him nor of Alison. The pioneers are (Clockwise from the top in chronological sequence: Giovanni Battista della Porta, William Charles Wells, Giovanni Battista Venturi, Charles Wheatstone, Ernst Heinrich Weber, Gustav Theodor Fechner, Heinrich Wilhelm Dove, August Seebeck, Anton Steinhauser, Silvanus Phillips Thompson, Lord Rayleigh and Diana Deutsch.

This observation excited the interests of Fechner (1860). He compared binocular single vision, based on stimulating corresponding retinal points, with binaural single hearing. However, Fechner's observations were directed to the effects of attention on discrimination. Whereas he was unable to distinguish between the sounds of two watches held next to one ear, when they were placed before separate ears they could not only be distinguished, but he could hear first one then the other. He likened this to rivalry between the ears. Unlike binocular rivalry, binaural rivalry involved shifts of location as well as perception.

Thus, it was several decades after Wells' (1792) 'thought experiment' that interest in binaural combination was again aroused, although his thoughts were not cited. In addition to the studies by Dove (1841), Seebeck (1846), Weber (1846) and Fechner (1860), Thompson (1877) conducted an experiment rather like that suggested by Wells: he produced beats binaurally by sounding tuning forks in each ear independently. He also noted that the apparent location of the sound was at the back of the head when the vibrations were out of phase. This was followed up by a second paper in which Thompson (1878) investigated the effects of pitch, phase, intensity, and quality on auditory localization. Contemporary research with modern auditory equipment has vindicated Wells' speculations. Deutsch (1979) presented component tones of a melody separately to the two ears and this disrupted the identification of melodic configurations in comparison to their simultaneous presentation to both ears.

Wells's insightful speculations about binaural hearing have been neglected, as have his studies on binocular visual direction and visual vertigo (Ono, 1981; Wade, 2000, 2003a; Wade, Ono, Mapp & Lillakas, 2011). One reason could have been that he did not pursue his speculations on dichotic listening, either experimentally or theoretically, and they were made in a book on vision rather than on hearing.

Müller (1843) described a procedure that a century later became a standard method for examining dichotic listening:

> When two persons address their speech to our opposite ears simultaneously, the two impressions conveyed to the sensorium become mixed; and it is only by great exertion of the attention, and by the aid of a difference of tone of the two voices, that we are enabled to follow the sounds of one exclusively, disregarding those of the other, which are then heard as a more or less indistinct murmur. (pp. 1307–1308)

Müller appreciated that attention was required to follow one of the messages, and from the 1950s, dichotic listening tasks were examined in the context of selective attention (see Cherry, 1961; Yost, 1997). Cherry (1953) presented different messages to each ear and noted that one could be followed; he called it the cocktail party phenomenon.

One area of closer parallel between dichoptic and dichotic studies is related to rivalry. Deutsch (1974, 2004) described an auditory illusion that was dependent upon the ear to which tones were presented; she called it the octave illusion. When alternating tones an octave apart are played out-of-phase to each ear most listeners experienced "a single tone oscillating from ear to ear, whose pitch also oscillated from one octave to the other in synchrony with the localisation shift" (Deutsch, 1974, p. 307). The illusion reflects an integration of signals from the two ears because the oscillation in tones is not confined to one ear. That is, a single tone is heard and it oscillates from one ear to the other.

Almost 70 years after Venturi's experiments on auditory localisation, Lord Rayleigh (John William Strutt) performed a similar study, but in ignorance of its predecessor. Rather than move around a listener (because the footsteps could be detected), he placed assistants in several directions and they produced sounds when instructed: "The uniform result was that the direction of a human voice used in anything like a natural manner could be told with certainty from a single word, or even vowel, to within a few degrees" (Rayleigh, 1876, p. 32). Similar results were found with tuning forks, although sounds from directly ahead or behind were confused. Differences between the intensities of sounds at each ear were thought to be involved, but calculations of the differences led him to question whether they were large enough to account for the power of discrimination.

Steinhauser (1877, 1879) built his theory of binaural hearing on an analysis of auditory localization. He stated that: "*the direction in which a source of sound is situated may be estimated by the different intensities with which a sound is perceived in the two ears*" (1879, p. 186). The pinna of each ear played a significant role in the differential intensities reaching the auditory canal, as he indicated graphically (Figure 7), and determined trigonometrically. Sounds within the angle D*n*C were referred to as direct because they were projected to each ear whereas those within the angles A*n*D or B*n*D were called mixed due to the direct stimulation of one ear relative to the other; indirect stimulation was from behind the head. He divided the whole of auditory space into three regions: "*in front*, the region of direct hearing; at *the two sides*, the regions of mixed hearing; and *at the back*, the region of indirect hearing" (Steinhauser, 1879, p. 272).

Alexander Graham Bell (1880) also performed an experiment similar to that of Venturi but with the added technical sophistication of the telephone. He was aware that "the difference between monaural and binaural audition is especially well marked when we attempt to decide by ear the locality of a particular sound" (Bell, 1880, p. 169). In order to pursue this difference experimentally he set up an arrangement of telephones receiving signals from one room and listened to in another (Figure 7). Telephone A was connected to C and B to D. They were separated by about the distance between the ears. A and B were in one room (EFGH) while C and D were in another. Speech from a person moving around room EFGH could be heard by the listener using either C and D or C or D alone. The listener was required to indicate the location within the room of the speaker. The initial experiments were conducted in London and they were extended on Bell's return to America using microphones in the room rather than telephones. He found that "the direction of a source of sound is less perfect by a single ear than by both ears" (1880, p. 175). He also found, like Venturi and Lord Rayleigh, that binaural sounds could be localized in the auditory axis but that those from straight ahead or behind were confused.

Bell had followed Thompson's experiments on binaural beats and they corresponded with one another about them as well as the pseudophone (Thompson & Thompson, 1920). Like Bell, Thompson (1882) examined auditory localization in the context of visual localization. Both were analyzed in terms of direction and distance (as Wells had advocated for vision almost a century earlier), and Thompson noted the differences between ears and eyes in terms of focusing, receptor layout, and motor control. The features involved in auditory localization were listed:

> There are four physical characteristics of waves of sound by which one sound is discriminated from another, viz:- (i) ***Intensity***, or loudness, depending upon extent or energy of the vibratory motions. (ii) ***Pitch***, or frequency, depending upon the rapidity of the vibratory motions. (iii) ***Phase*** of the vibratory motions, as to whether moving backward or forward or at any other state. (iv) ***Quality***, or timbre, depending upon the degree of complexity of the vibratory motion. The third of these physical characteristics is one for which the single ear possesses no direct means of perception. (Thompson, 1882, p. 408)

Thus, Thompson argued that phase differences alone were in the province of binaural hearing and so served the function of localizing the direction of sounds in space. Distance presented a more complex problem, and he considered that: "In the case of known sounds we doubtless judge chiefly of their distance by their relative loudness, the intensity decreasing inversely as the square of the distance" (1882, p. 415). Nonetheless, Thompson did entertain the possibility of 'acoustic parallax' playing a role in its determination for sounds at short distances.

Further study was inhibited by debates regarding absence of spatiality in hearing (Boring, 1942). When auditory localization was examined at the end of the 19th century it was dominated by controversies over whether intensity or temporal differences serve as cues, but there were researchers also concerned with non-theoretical experimental questions (Pierce, 1901). Rayleigh (1907) proposed a duplex theory of binaural localization: it was possible due to interaural differences in intensity and time of arrival of the sounds. Later it was recognized that the two bases for localization operated at different frequency bands; one for high frequency tone serving as an intensity cue and the other for low frequency tones serving as a temporal cue (von Hornbostel & Wertheimer, 1920). There now exists a large body of binaural phenomena but they are based on relatively recent studies (Wade & Deutsch, 2008).

Distinctions between where a stimulus is located and what its identity is have come to the fore in studies of both vision and hearing. In the case of vision the distinction has been sustained by evidence from different streams of cortical processing (Ungeleider & Mishkin, 1982), whereas in audition it has been led by psychophysical studies (Deutsch, 1976). Moreover, the visual distinction was not sustained by binocular phenomena while that in audition was based on binaural studies of the octave illusion. Modern studies of binaural hearing owe much to the pioneers of these topics who are shown in Figure 8. It will be noted that many who worked on binaural hearing were pioneers of binocular vision, too.

Conclusion

The history of research on vision differs from that on hearing and this applies more markedly to binocular vision and binaural hearing. Vision has been dominated by cataloguing observations whereas hearing has focussed on defining the stimulus – sound. The physical characteristics of sound were appreciated long before those of light. Sounds were produced by vibrating bodies and details of such vibrations were elaborated over centuries. The nature of light was much more enigmatic; for some it had its origin in the eye itself whereas others adopted more general interpretations regarding its origin. Speculations regarding vision involved spatial images which resembled the objects perceived. Spatial dimensions could be measured and manipulated in pictorial stimuli. Moreover, it was appreciated that what could be seen with one eye differed slightly from that seen by the other. Hearing, on the other hand, is temporal and concepts of images were not incorporated into theories. Differences in the sounds experienced by one ear were rarely compared to those in the other. Fractionating time into smaller intervals proved much more difficult than fractionating space. Moreover, temporal resolution in hearing was much more acute than in seeing with the opposite applying to spatial resolution. Thus, seeing and hearing were distinguished by knowledge of the sources of stimulation as well as by the concepts used to account for their reception.

Over this large timescale, very little was written about binaural hearing, in comparison to the wealth of binocular phenomena that were then discussed and investigated experimentally. Things were to change fundamentally in the 19th century both in terms of the instruments that can differentially stimulate two eyes or two ears and the manner in which the new phenomena were interpreted.

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