BINAURAL HEARING—BEFORE AND AFTER THE STETHOPHONE

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The late eighteenth century witnessed many revolutions in both science and society, but one of the former remains relatively unsung—the revolution in binaural hearing. The experimental endeavors of Ernst Florens Friedrich Chladni (1756–1827) shown in Fig. 1 are well known.[1] Indeed, Chladni has been called the father of acoustics. Chladni investigated the characteristics of vibrating strings and plates and advanced the physical analysis of sound.[2-4] However, he paid relatively little attention to the then contemporary deliberations on binaural hearing. In his *Akustik* of 1802 he did cite the experiments of Giovanni Battista Venturi (1746–1822), and repeated Venturi's suggestion that localization of sounds was dependent upon inequalities at the two ears. Despite the fact that between 1796 and 1802, Venturi[6-9] described essentially the same four experiments in French, German and Italian, few (other than Chladni) took note of them. Even earlier, in 1792, William Charles Wells (1757–1817) examined some theoretical aspects of binaural hearing.[10,11] We here describe the work of Wells and Venturi on binaural hearing, as well as that of others in the early nineteenth century, particularly Alison and his stethophone.[12]

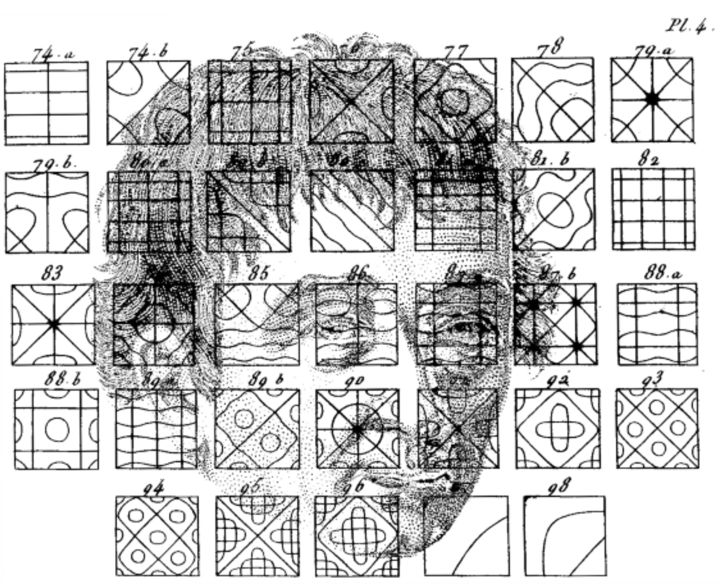

Fig. 1. "Chladni figures" by Nicholas Wade. The portrait of Ernst Chladni is embedded in an array of acoustic figures taken from his "Traité d'Acoustique."[4] The portrait is derived from a frontispiece engraving in John Tyndall's book on "Sound."[5]

The stethophone was invented in 1859 to listen to different sounds separately with each ear. It was the auditory equivalent of the stereoscope. In much the same way that binocular vision was studied theoretically and experimentally before the invention of the stereoscope, binaural hearing was examined before suitably selected sounds could be delivered to each ear by means of the stethophone. The early studies on binaural hearing were informed by comparisons with binocular vision, and so we introduce this history with a contrast between these two aspects of integrated perception.

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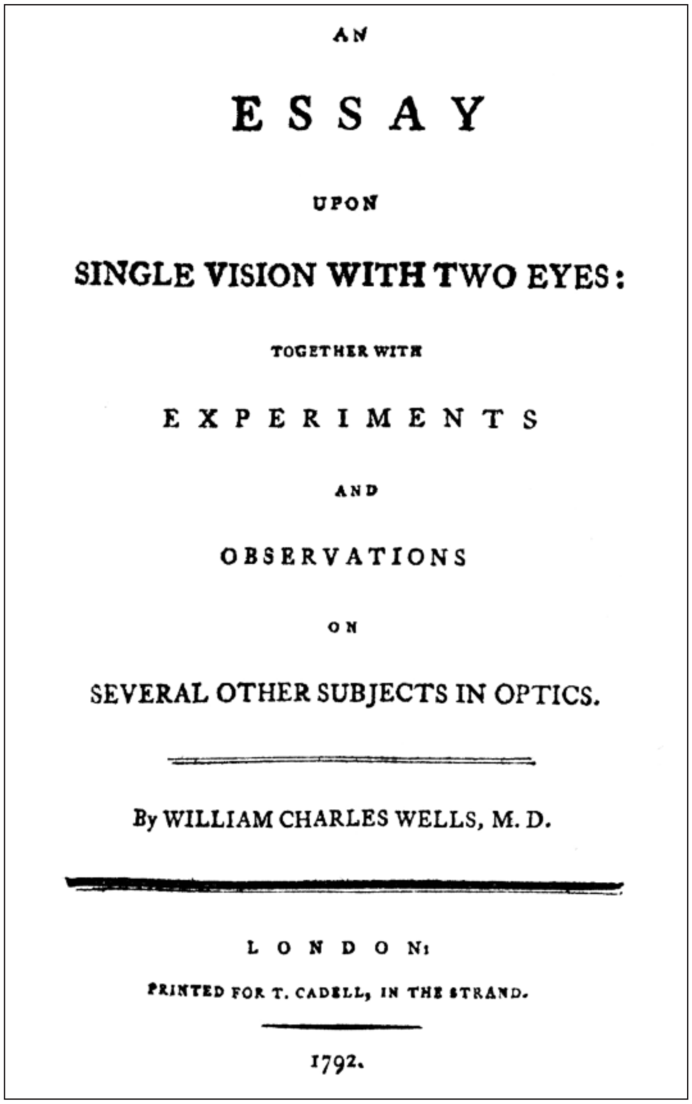
Sound and sight

The nature of sound was appreciated long before that of light. First, sound was never associated with its production in the ears, as light was in the eyes.[13] It was not until the seventeenth century, with Kepler's analysis of optical image formation in the eye, that a receptor theory of light was generally accepted. Prior to that, extramission theories (that light was produced within the eye) were accepted. This was principally based on the observation that light could be seen in the dark when pressure was applied to the eye. Sound, on the other hand, has been associated with vibrations of bodies and their transmission through a medium at least since the time of the ancient Greeks. In short, the ear was not endowed with the generative properties that were attributed to the eye. Secondly, the nature of the stimulus for sound was appreciated (if not fully understood) before that of light. The seventeenth century disputes between corpuscular and wave theorists remain unresolved, as the duality of light is still with us. Thirdly, stimulus manipulations of sound have a longer history than those for light. Light has been examined in terms of its reflections and refractions for centuries, but the nature of the stimulus remains a mystery.

Paradoxically, although much was known about the nature of sound in early times, experiments on hearing lagged behind those on vision until the twentieth century. In particular, differences in the patterns of stimulation at each ear were not examined with the consistent concern that was applied to differences in the stimuli to each eye. There were at least three reasons for this: First, phenomenal differences could readily be perceived in vision: opening one eye and then the other made apparent the differences between them. These were remarked upon and examined empirically by Ptolemy in the second century and by Alhazen in the tenth. They were illustrated in the eighteenth century, although the involvement of spatial differences in the images projected to each eye in stereoscopic depth perception was not understood until the nineteenth century.[14] Similarly, double vision of a single object could readily be experienced by either crossing the eyes or by pressing one of them with a finger; Aristotle described the consequences of the latter. However, phenomenal differences between the ears were more difficult to discern; the most common procedure was to cover one ear or to stop it by means of a finger, and this method was employed in the late eighteenth and early nineteenth centuries.



AN

ESSAY

UPON

SINGLE VISION WITH TWO EYES:

TOGETHER WITH

EXPERIMENTS

AND

OBSERVATIONS

ON

SEVERAL OTHER SUBJECTS IN OPTICS.

By WILLIAM CHARLES WELLS, M. D.

LONDON:

PRINTED FOR T. CADELL, IN THE STRAND.

1792.

Fig. 2. The title page of Wells's essay in which he described his thought experiments concerning the perceptual combination of sounds at the two ears.

Secondly, the mobility of the eyes in both version and vergence is not matched in humans with a corresponding mobility of the ears. Moreover, abnormalities of binocular eye movements, as in strabismus, were an early topic of medical concern. The consequences of losing an eye for spatial vision were remarked upon in the seventeenth century, with a corresponding appreciation of the advantages that accrue to having two functioning and aligned eyes.[15] Thirdly, the manipulation of spatial patterns of illumination was much easier than that for temporal differences in sound patterns. Even before the invention of the stereoscope in the 1830s by Charles Wheatstone (1802–1875), several means of presenting different stimuli to the two eyes were available. These consisted of bifixating a close point while presented with two more distant and horizontally displaced patterns, viewing two objects through an aperture, placing a prism before one eye or viewing two patterns on opposite sides of a septum, or looking down two viewing tubes.[16] The stereoscope revolutionized studies of binocular vision—it provided both a device for controlling the stimulus to each eye and a means for establishing the link between retinal disparity and depth perception. With the aid of the stereoscope, disparate patterns could be produced with ease, and the consequences of viewing them could be determined.

When binaural instruments were introduced in the nineteenth century, they were fashioned on binocular instruments such as the stereoscope and pseudoscope. However, it was not until the invention of headphones and precise electronic control of sounds that a detailed investigation of binaural hearing became feasible. Nevertheless, studies of binaural integration did take place before precise stimulus control became available. In this article we review these early studies and speculations, and relate them briefly to more recent work in the field.

Early speculations and informal studies

The seeds of the revolution in binaural hearing were sown by an American and an Italian, long before the stethophone was devised, and their studies were both theoretical and empirical. The source of this interest derived from inquiries into binocular integration—more specifically, it was stimulated by studies of binocular color mixing. In contrast to the lawful combination of colors from different regions of the spectrum, it was found that presenting different colors to each eye did not follow similar rules. The colors tended to engage in rivalry rather than fusion.[15] Among those who later pursued binocular color combination were Wells, Venturi, Wheatstone, Ernst Heinrich Weber (1795–1878) and August Seebeck (1805–1849), and it is notable that all these thinkers were to consider similar aspects of binaural combination.

Wells was born in Charlestown, South Carolina, to Scottish parents; he returned to Scotland for his education and graduated in medicine from Edinburgh University and eventually practiced in London. He is best known for his theory of the formation of dew, and he also anticipated Charles Darwin in proposing a theory of natural selection.[11] A footnote in his monograph on binocular visual direction (the title page of which is shown in Fig. 2) reads: *"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*

Fig. 3. Detail of a portrait of Giovanni Battista Venturi painted by Prospero Minghetti in 1818 (reproduced by kind permission of the Musei Civici, Reggio Emilia). In the 1790s Venturi conducted experiments on sound localization while blocking one ear with his finger.

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."[17] Wells did not conduct such experiments, but reached his conclusions on the basis of his observations of binocular color combination. His remarkably prescient prediction concerning the presentation of two streams of tones in alternation at the two ears has only recently been examined, as will be detailed below.

Venturi (Fig. 3) was born near Reggio Emilia; he became professor of physics at Modena and Pavia and is best known for his work on fluid mechanics. His studies of Leonardo da Vinci's manuscripts resulted in a radical revision of the artist's scientific and technological genius.[18] Venturi wrote extensively about optics and its history, and it is in an appendix to one of his monographs on color that he described experiments on auditory localization using one or two ears.[8] He had examined binocular color combination with blue and yellow papers, and arrived at a firm conclusion: *"I have never experienced a third color from the two overlapping colors."*[19] In his experiments on auditory localization he compared listening with both ears to listening with one ear blocked by a finger. He concluded that spatial localization was only possible with both ears, and he surmised that this was based on amplitude differences between the two ears: *"Therefore the inequality of the two impressions, which are perceived at the same time by both ears, determines the correct direction of the sound."*[20] Venturi's experiments were essentially repeated and confirmed by Lord Rayleigh (1842–1919), although Rayleigh appeared to have been unaware of them.[21]

Wheatstone (Fig. 4) is famous particularly for his work in electricity, measuring its velocity and devising a bridging means of measuring resistance. In the context of perception, he is best known for his invention of the stereoscope, though

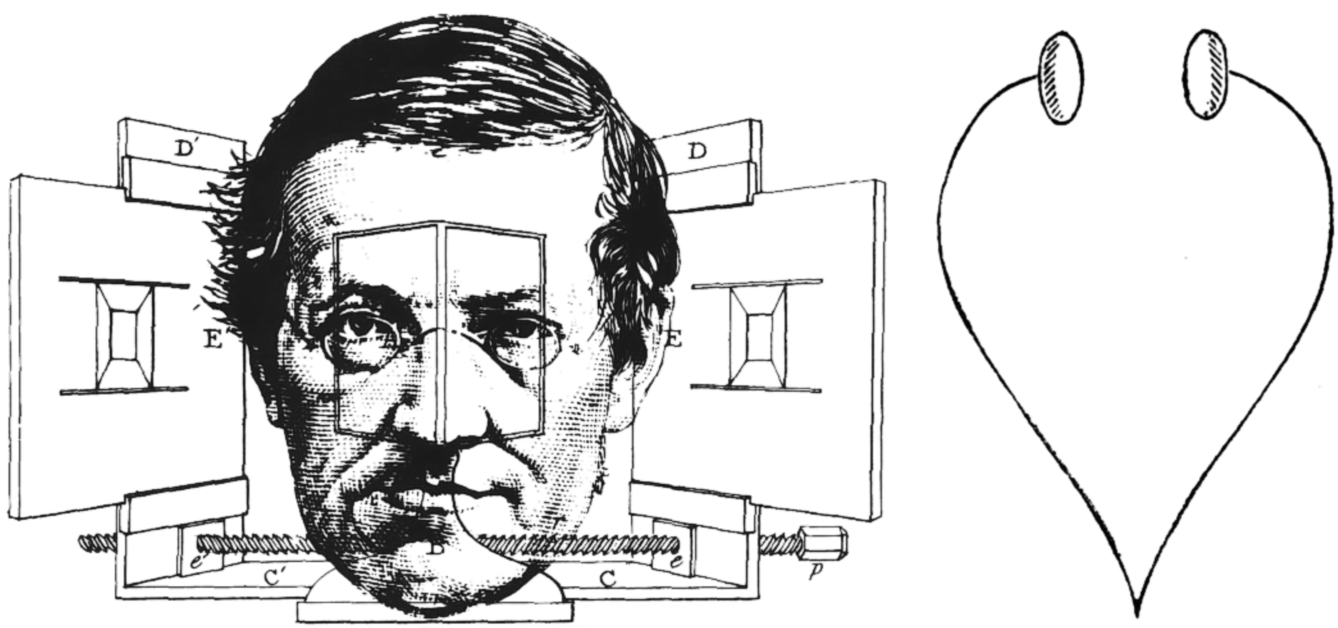


Fig. 4. Left–"Stereoscopist" by Nicholas Wade. Charles Wheatstone is shown with his eyes in the mirrors of his stereoscope. Wheatstone's portrait is derived from an engraving in The Illustrated London News marking the award of his knighthood; the diagram of the stereoscope is taken from Wheatstone's original article.[26] *Right–Wheatstone's diagram of a simple binaural instrument of his invention that he called a microphone.*[27] *He 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."*

Fig. 5. Left– detail of a portrait of Ernst Heinrich Weber. Right–"Weber colour fractions" by Nicholas Wade. The same portrait of Weber is embedded in a pattern representing psychometric functions. His face is present in both the upper and lower parts of the design, corresponding to the upper and lower thresholds.

he commenced his researches in audition, and was led to the study of vision through the visual expression of acoustic phenomena. Wheatstone was born in Gloucester and joined the Wheatstone family business, which was concerned with the manufacture of musical instruments. He was appointed to the chair of experimental philosophy at King's College, London, at the age of 32, and held the post for the rest of his life.[22,23] He invented a number of musical instruments, the most popular of which was the concertina. In the 1820s, he published work on visual persistence, and constructed a philosophical toy which traced beautiful patterns—called the kaleidophone, after Brewster's kaleidoscope.[24] The kaleidophone was constructed to amplify the vibrations of rods 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 acoustic phenomena.[25] He also invented one of the earliest binaural instruments that he called a microphone as shown in Fig. 4, together with his portrait.

Wheatstone also conducted experiments with tuning forks presented to different ears: *"It is well known, that when two consonant sounds are heard together, a third sound results from the coincidences of their vibrations; and that this third sound, which is called the grave harmonic, is always equal to unity, when the two primitive sounds are represented by the lowest integral numbers. This being premised, 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."* [29]

Wheatstone's description concerning the perceptual fusion of harmonically related tones addressed a related issue to those addressed by Wells.[10] The observations of both Wells and Wheatstone went unheeded however, and were not cited by the German researchers who addressed similar issues at around that time and in the following decades. One such was Weber (Fig. 5), who is well known as one of the founders of psychophysics.[30] Weber was born in Wittenberg where he studied medicine. Most of his academic life was spent in Leipzig, where he held chairs—first of anatomy and then of physiology. Chladni was a frequent visitor to the Weber household and, with his brother Wilhelm, Weber wrote a book on wave theory.[31] He also published two monographs on the senses. In the first, he described binocular color mixing, concluding that the two colors appear as one however, he did not experience green when a blue glass was in front of one eye and a yellow in front of the other. When he was examining binaural integration, the import of Wheatstone's stereoscopic observations was being absorbed, but his descriptions of binaural combination were overlooked.

Heinrich Dove (1803–1879) had considered the operation of the two ears in a manner analogous to two eyes, and described an experiment, similar to that of Wheatstone, in which different tuning forks were held by the side of each ear.[32] He reported that beats were audible under these circumstances. Yet Weber reached the opposite conclusion when he carried out a similar study using pocket-watches ticking at slightly different rates. If they were both placed next to the same ear, then the beats could be heard: *"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."*[33] Weber addressed this problem in the context of differences between sensation and interpretation, and speculated that two different auditory sensations could not be perceived simultaneously.

In the same year Seebeck reported experiments on listening to different sounds in each ear.[34] He was an authority on color vision, and had investigated binocular color mixing however, his experiences did not accord with those reported by others. He observed a mixture of colors rather than rivalry between them. Seebeck's experiments were triggered by Dove's descriptions of stimulating two eyes and two ears. Seebeck used sirens as well as tuning forks to stimulate the ears, and reported that each sound could be localized to the ear receiving it, and that the two sounds were not combined.

Weber's speculations on the involvement of attention later evoked the interest of Gustav Theodor Fechner (1801–1887), shown in Fig. 6. Fechner became interested in the combination of sounds presented to different ears. Not only did he find it impossible to hear beats when watches, with slightly different ticking rates, were placed at each ear, but he also described a type of rivalry between the two sounds—he heard one and then the other in succession.[35] He found the same effects when he used earflaps to surround the watches—a move towards the use of earphones. This provided further evidence for his comparison between hearing with the two ears and seeing with the two eyes. In pursuing this analogy, he questioned the equivalence between presenting different colors to each eye and different sounds to each ear. Fechner repeated the experiments with tuning forks, after the manner of Wheatstone[27] and Dove[32], and obtained results that were similar to those of Wheatstone, and not to those of Dove. (Fechner also noted that the majority of people have poorer hearing in the right ear than in the left, and indicated

Fig. 6. Left– detail of a photogravure of Gustav Theodor Fechner from Kunke.[36] Right–"Fechner coloured" by Nicholas Wade. The portrait on the left is also present in the psychometric functions on the right—Fechner can be seen in the area of uncertainty of the curves.

that any experiments using two ears should take note of the ear to which stimuli are presented.)

The invention of the stethophone and beyond

An important advance in the study of binaural hearing occurred with the invention of the stethophone (Fig. 7) by Somerville Scott Alison (1813—1877). His communication of this invention to the Royal Society was read by John Tyndall (1820—1893) on 22 April 1858 and it was printed in their Proceedings in the following year.[12]

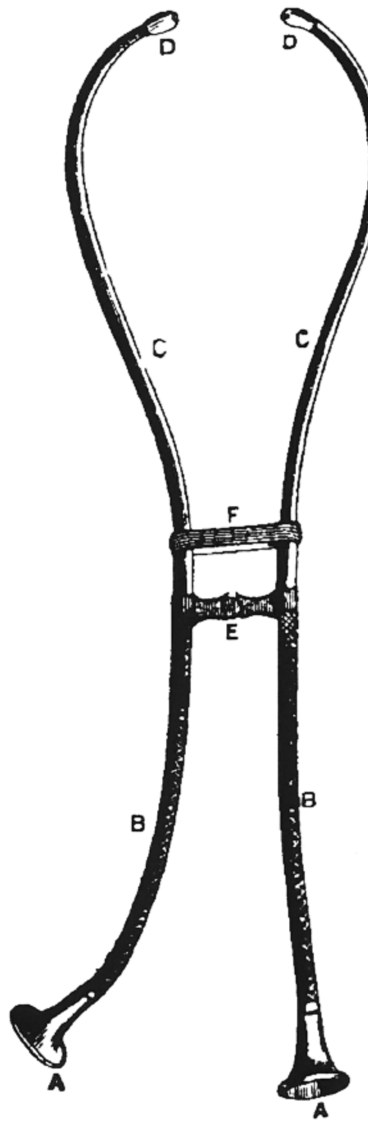


Fig. 7. Alison's stethophone as illustrated in his original article: "The tubes are composed of two parts nearly equal in length, one near the ear-knob, made of metal (C); while the other part, near the collecting-cup, is made of metal wire (B), to impart flexibility. The ear-end is curved, so as to 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."[37]

Alison was born in Edinburgh, and graduated from its Medical School in 1833. He moved to London in 1841, where he set up practice and specialized in diseases of the heart and lungs. It was in this context that he invented the stethophone, which was derived from the stethoscope—an invention of René Théophile Hyacinthe Laennec (1781–1826).[38] Laennec's stethoscope was a simple tube or cylinder that could amplify sounds from the chest when placed between ear and chest. The cylinder could be made of paper, but wood proved more durable. Adapting a single tube which then connected to the two ears appeared shortly afterwards, although its adaptation was more for convenience than for any binaural benefits: *"The instrument adapted to this purpose consists of a tube, connected at its middle at right angles to the cylinder, to be applied to the patient, and connected at its moveable extremities to two tubes."*[39]

Alison's stethophone had independent ear tubes, so that different sounds could be listened to with this instrument: *"The differential stethophone is simply an instrument consisting of two hearing-tubes, or trumpets, or stethoscopes, provided with collecting-cups and ear-knobs, one for each ear respectively. The two tubes are, for convenience, mechanically combined, but may be said to be acoustically separate, as care is taken that the sound, once admitted into one tube, is not communicated to the other."*[40]

In describing his experiments using the stethophone, Alison referred back to those of Wheatstone: *"Mr. Wheatstone shows that a vocal sound is heard louder in that ear that is closed, say with the finger, than in the other. He also shows, that the sound of a tuning-fork placed upon the head is heard louder in that ear which is closed than in the other which remains open, even though the tuning-fork may be brought nearer the open ear than the closed one."*[41] Here, Alison was referring to Wheatstone's report of experiments in which he described the microphone, and his binaural investigations with tuning forks.[27] This was the only study that Alison found relevant to his own, using the stethophone. He presented sounds of different intensity to each ear and found that the more intense one was heard in the ear receiving it. *"Sound, as is well known, if applied to both ears in equal intensity, is heard in both ears; but it will be found, if the intensity in respect of one ear be moderately yet decidedly increased, by bringing the sounding body nearer that ear than the other, or otherwise, as by the employment, in respect to one ear, of a damper or obstructor of sound, or in respect to the other ear, by the employment of some intensifier, or good collector or conductor of sound, the sound is heard in that ear only which is favoured and has the advantage of greater intensity."*[42]

The principal sound sources used for Alison's experiments employing the stethophone were watches (although he did not cite Weber's[30] or Fechner's[34] reports using pocket watches). Most of Alison's studies involved a single watch, the intensity of which was varied to each ear. The watch was heard in the ear receiving the more intense sound. When two different watches were employed, one to each ear: *"the sounds of both watches are heard, but the sound from one is heard in one ear, and the sound from the other is heard in the other ear."*[43] On the basis of the experiments 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."*[44]

Alison also conducted an experiment that can be related to those proposed by Wells[10] and also to that conducted by Wheatstone[27] in which components of sounds were presented to different ears, both simultaneously and in succession: *"In order to effect a division of a compound sound, it is only necessary that the two sounds of which it is composed may respectively be heard at certain points, in greater and lesser intensity, and that the respective cups of the stethophone be placed at these points…For example, a compound sound composed of the two sounds of two watches placed together upon a table, with the unassisted ear is distinctly heard in its compound state, and cannot be divided into its constituent two*

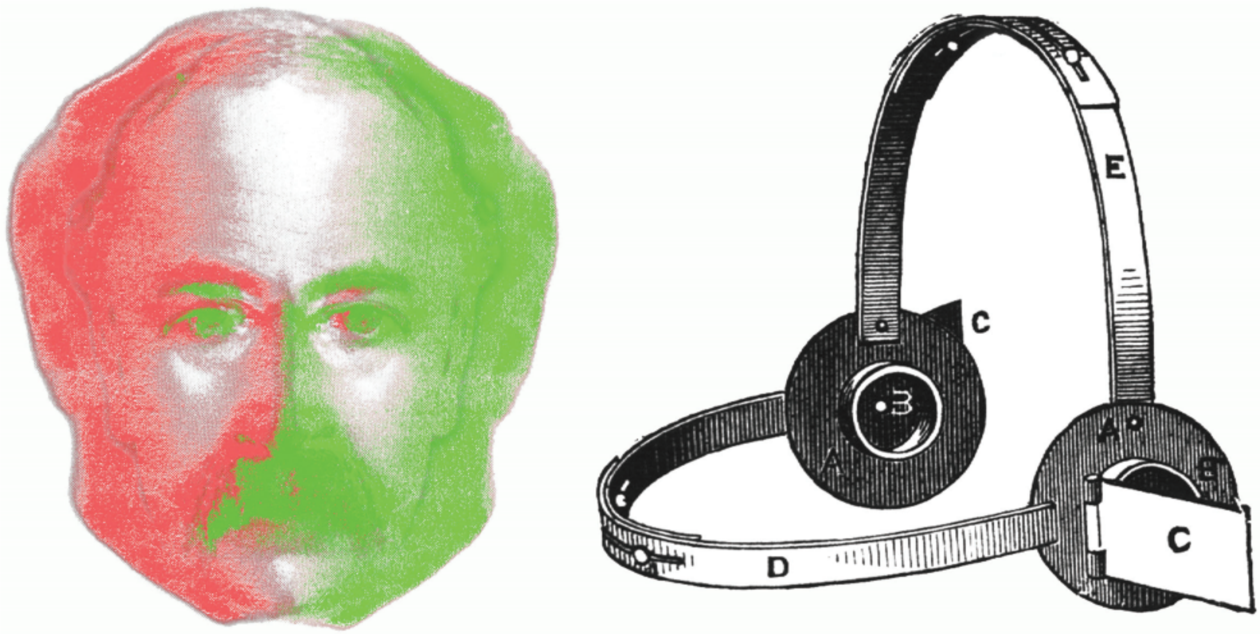


Fig 8. Left–"Pseudoscopic Thompson" by Nicholas Wade. Silvanus Phillips Thompson is shown with his left and right eyes superimposed. Right–his illustration of the pseudophone which he described in the following way: "The simple instrument for which the author suggests the name Pseudophone consists of 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."[52]

parts."[45] The stethophone made such experiments both easier to perform and with more precise separation of the sound sources than had been possible beforehand. Alison then applied these principles to the practice of auscultation in medicine.

Alison soon afterwards introduced the term *binaural.*[46] It was applied to his differential stethophone, which he subsequently referred to as a bin-aural stethoscope. Later, Silvanus Thompson (1851–1916), shown in Fig. 8, used the term *binaural* in the title of an article concerned with similar experiments to those of Fechner[34] with tuning forks (though he was unaware of this earlier work). He presented a tone of slightly fluctuating pitch to one ear (using an India-rubber tube) and a standard tuning fork to the other ear.[47] Interference beats could be heard binaurally, but tones differing in phase could not. He confirmed these findings in a second paper,[48] and described the experience that the combined tone was localized within the head. In a further article,[49] he described his invention of the pseudophone, which was modeled on Wheatstone's pseudoscope.[50] He wrote: *"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."*[51]

At about the same time, Anton Steinhauser (1802–1890) presented his theory of binaural audition in a short monograph.[53] It was translated into English by Thompson, and it proposed that the directions of sounds were determined principally by differences in intensity between the ears. This is essentially the same conclusion as had earlier been reached by Venturi[6-9]. Steinhauser stated that the area of binaural hearing was a novel one: *"The second branch of the subject [binaural audition], which has never, to my knowledge, been yet developed, has to discuss the general question of hearing, with respect in particular to the circumstance that it is performed with two ears. It is concerned, further, in deciding what part binaural hearing plays in the various phenomena of hearing in general, and the various advantages thereby gained."*[54] (The novelty of this area was attested by the absence of any references in Steinhauser's earlier monograph.)

Alison's invention of the stethophone did not have the impact of Wheatstone's stereoscope— there was no sudden surge of studies in the way there were after the announcement of the stereoscope. On the other hand, Thompson's experiments did herald a new departure. That is, rather than the stethophone, it was Thompson's use of rubber tubes to deliver sounds separately to each ear, and his invention of the pseudophone, that transformed the experimental study of binaural hearing. The characteristics of the monaural stimuli could now be specified and delivered more precisely, and the factors involved in sound localization could be fractionated (see also the later work of Thompson[55] and Rayleigh[56]). The renewal of interest in matters binaural even led to the introduction of a specific terminology for stimulating the ears. Carl Stumpf (1848–1936) distinguished between *dichotic* which referred to the stimulation of each ear with a different stimulus and *diotic*—the simultaneous stimulation of each ear with the same stimulus.[16,57]

Related twentieth century observations

The development of electronic technology at the turn of the twentieth century enabled researchers for the first time to study binaural interactions with the precision required to arrive at firm conclusions. The early speculations and informal experiments described above addressed at least five separable issues concerning binaural integration: The integration of input from the two ears to localize sounds; the integration of tones presented in rapid succession to the two ears to perceive melodies; the perceptual fusion of simultaneous input to the two ears, particularly to determine pitch; the issue of binaural rivalry; and binaural beats. All these have been examined in recent times, and we briefly examine those recent experiments that are particularly related to the earlier work.

Largely for technological reasons, research on the localization of sounds in the early and middle parts of the twentieth century focused on very simple sound signals, such as pure tones and noise. Much of this work was inspired by Lord Raleigh's *duplex theory* of binaural perception.[56] Sound localization by the binaural system (according to Raleigh's duplex theory) is based largely on two types of cue— interaural time and intensity differences—the latter particularly at low frequencies. The use of these cues has been confirmed and studied extensively (see Stern *et al*[58] for a review). For single sounds presented in isolation, the binaural system has been shown capable of utilizing interaural time-differences of around 10 microseconds, and interaural intensity-differences of around 1 dB.[59,60]

With further improvements in instrumentation and analysis, considerable interest also developed in the involvement of spectral cues for sound localization, particularly along the vertical and front-back planes.[61] Attention here has focused on spectral differences produced by the head, and by the outer and middle ears. The insertion of probe microphones in the ear enabled the determination of the transfer function from the sound source to the eardrum. Using this technique, it has been found, in particular, that interaural intensity differences for different frequency bands provide important cues to the localization of sounds coming from different directions.[62,63] In parallel with these experimental developments, sophisticated models of binaural interaction for sound localization were developed.[58]

As described above, much of the early work concerning binaural integration was addressed to the nature of the sounds that were perceived, independently of how they were localized. The early thought experiment proposed by Wells[10] concerning integration of melodic patterns with tones presented in alternation to the two ears was very similar to one carried out by Deutsch,[64] who was, at the time, unaware of this earlier work. In this experiment, continuously repeating melodies were presented at a rate of roughly 6 per second, and listeners were asked to identify them. When the tones were presented diotically, the identification rate was very high. However, when the tones were switched haphazardly between the ears, listeners were unable to integrate them into a single perceptual stream, and so to identify the melody. This finding was in accordance with the prediction made by Wells.[10]

However, the reason for this difficulty was not as Wells had surmised. When a low drone was presented contralateral to the ear receiving each melody component, identification again rose to high levels. From this and other control conditions it was concluded that when each ear received input separately, tones were organized by spatial location; however, when presentation of the contralateral drone enabled an alternative organization by pitch proximity, listeners instead integrated the tones from the two ears in accordance with this principle. Thus the difficulty in melody identification found in the primary experiment was not due to an inability to integrate information across ears at fast rates, but rather to a grouping decision made by the auditory system that could be overridden by other cues (see also Bregman[65]).

Work on integrating streams of speech that were switched between the ears can be interpreted in the same light. Cherry and Taylor[66] presented a single stream of speech

Nicholas Wade combines art, science and history in his "perceptual portraits." His training is in visual psychology and he developed an interest in the interaction between visual art and visual science from his analysis of "op art." Having taught himself how to produce works in this genre, he combines drawn designs with photographic images, often producing works that are at the limits of visibility. His art work has been published in his books: *The Art and Science of Visual Illusions* (Routledge and Kegan Paul, 1982), *Visual* Allusions: *Pictures of Perception* (Erlbaum, 1990), *Psychologists* in *Word and Image* (MIT Press, 1995) and *Circles: Science, Sense and Symbol* (Dundee University Press, 2007). He is currently working on *Galileo and the Senses* with Marco Piccolino, which will be published by Oxford University Press.

The faces shown in perceptual portraits are not always easy to discern—the viewer needs to apply the power of perception in order to extract the facial features from the design which carries the portraits. They generally consist of two elements—the portrait and some appropriate motif. The nature of the latter depends upon the endeavours for which the portrayed person was known. Thus, Chladni (Fig. 1) is embedded in his acoustic figures; Wheatstone (Fig. 4) is in his stereoscope; Weber (Fig. 5) is shown three times but two portraits are near to threshold in curves that correspond to psychometric functions (the colors represent those he examined for binocular color rivalry); Fechner (Fig. 6) is hidden in the area of uncertainty of psychometric functions; and Thompson (Fig. 8) is combined in complementary colors in the normal head orientation and left-right reversed, so that the eyes are reversed as in pseudoscopic vision. Similar principles have been applied to the portraits of the authors (see page 27). That of Wade is based on binocular interaction as the centers of the intersecting circles that carry the dimly defined face are located at each of the eyes. The second is of Deutsch. It alludes to binaural integration with two waveforms approaching the sides of the head and combining in the midline, which corresponds to the midline of the embedded portrait.

Some examples of perceptual portraits can be found at:
http://www.perceptionweb.com/wade/
and in many of the editorial essays in *Perception*; see:
http://www.dundee.ac.uk/psychology/njwade/

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that switched continuously between ears. At slow switching rates, listeners could easily follow the speech however, as switching rates became faster, intelligibility dropped considerably, with a maximum dip at a switching rate of 3 cycles per second. The authors interpreted their findings as reflecting a limit to the rate at which attention could switch between ears. However, it was later found that when noise was presented to the ear contralateral to the one receiving the speech signal, so that both ears received input simultaneously, performance rose again to a high level, showing that a slow switching mechanism could not account for the results.[67]

The above experiments can also be related to that of Weber[30] on the perceived ticking of two pocket watches that were placed one to each ear. Weber's experiment is perhaps even more closely related to one by Axelrod and coworkers[68] who asked listeners to compare the repetition rates of two series of clicks under various conditions. When the clicks were presented to the two ears in alternation, their rates were considerably underestimated relative to monotic presentation, and the degree of underestimation increased with increasing presentation rate. We may surmise that in the dichotic condition the perceived rate was a compromise between the rate perceived on listening to each ear separately and that perceived on listening dichotically.

Concerning Wells' early speculation[10] that different sounds presented simultaneously but separately to the two ears would not coalesce perceptually, recent work has shown that binaural fusion can indeed occur, particularly for sounds built on the same fundamental.[69] More specifically, the early suggestion by Wheatstone[27] that presenting two harmonics separately to each ear would not result in the perception of the fundamental has been disconfirmed. When two adjacent harmonics of the same fundamental are fed to different ears, listeners can identify the pitch of the fundamental,[70] and the identification of the pitch of a two-tone complex with missing fundamental is only weakly affected by whether the components are fed to the same ear or to different ears.[71] As a related finding, the contribution of a single mistuned harmonic to the pitch of a complex tone was almost as great when it is presented to a different ear as when it is presented to the same ear.[72]

As described above, early thinking about binaural fusion also considered binaural rivalry that was stimulated by work on the simultaneous presentation of different colors to each eye. It has been shown recently that for certain dichotic configurations, the listener tends to follow the pitches presented to one (dominant) ear rather than the other, and this can happen even when the amplitude of the signal to the non-dominant ear is considerably higher in amplitude.[73,74]

Dove's early report of the existence of binaural beats has been confirmed by twentieth century studies that showed that such beats were heard at low rather than high frequencies, and were most salient at frequencies around 400-600 Hz.[75]

The investigations of Wells, Venturi, Alison and others on binaural hearing were conducted without the instruments that could adequately control the stimuli and their delivery to the ears. The questions that they posed have been addressed in the twentieth century and their thoughtful conjectures have been confirmed in some cases and disconfirmed in others. Their revolutionary research should be applauded because of the leaps of their imaginations—they used their (binocular) vision to derive insights into their (binaural) hearing.

Conclusion

The study of binocular vision has had a profound influence on that of binaural hearing. Both Wells[10] and Venturi[6-9] were led to the examination of binaural hearing following their studies of dichoptic color mixing. However, it proved more difficult to manipulate the temporal characteristics of sound stimuli than the spatial aspects of light. Alison's stethophone[12] could have opened the way to more systematic studies of binaural hearing, but it was Thompson's pseudophone[49] that was to have a greater impact. Modern studies have drawn attention to complexities of the binaural stimuli that were unknown to its early pioneers.**AT**

References

1 R. T. Beyer, *Sounds of Our Times: Two Hundred Years of Acoustics* (American Institute of Physics, Melville, 1998).
2 E. F. F. Chladni, *Entdeckungen über die Theorie des Klanges* (Weidmanns Erben und Reich, Leipzig, 1787).
3 E. F. F. Chladni, *Die Akustik* (Breitkopf und Härtel, Leipzig, 1802).
4 E. F. F. Chladni, *Traité d'Acoustique* (Courcier, Paris, 1809).
5 J. Tyndall, *Sound. A Course of Eight Lectures Delivered at The Royal Institution of Great Britain* (Longmans, Green, London, 1867).
6 J. B. Venturi, "Considérations sur la connaissance de l'étendue que nous donne le sens de l'ouïe," Magasin Encyclopédique, ou Journal des Sciences, des Lettres et des Arts **3**, 29-37 (1796).
7 J. B. Venturi, "Betrachtungen über die Erkenntniss des Raums durch den Sinn des Gohörs," Magazin für den neuesten Zustand der Naturkunde **2**, 1-16 (1800).
8 G. Venturi, "Riflessioni sulla conoscenza dello spazio, che noi possiamo ricavar dall'udito," in *Indagine Fisica sui Colori by G. Venturi* (Tipografica, Modena, 1801), pp. 133-149.
9 J. B. Venturi, "Betrachtungen über die Erkenntniss der Entfernung, die wir durch das Werkzeug des Gehörs erhalten," Archiv für die Physiologie **5**, 383-392 (1802).
10 W. C. Wells, *An Essay upon Single Vision with two Eyes: together with Experiments and Observations on several other Subjects in Optics*. (Cadell, London, 1792).
11 Wells's book on binocular single vision, as well as his autobiographical sketch, have been reprinted in: N. J. Wade, *Destined for Distinguished Oblivion: The Scientific Vision of William Charles Wells* (1757-1817) (Kluwer/Plenum, New York, 2003).
12 S. S. Alison, "On the differential stethophone, and some new phenomena observed by it," Proceedings of the Royal Society of London **9**, 196-209 (1859).
13 N. J. Wade, "Light and sight since antiquity," Perception **27**, 637-670 (1998).
14 N. J. Wade, "On the late invention of the stereoscope," Perception **16**, 785-818 (1987).
15 N. J. Wade, *A Natural History of Vision* (MIT Press, Cambridge, MA, 1998).
16 N. J. Wade, and H. Ono, "From dichoptic to dichotic: historical contrasts between binocular vision and binaural hearing," Perception 3**4**, 645-668 (2005).

17 Ref 10, p. 46; Ref 11, p. 88.
18 W. Bernardi, P. Manzini, and R. Marcuccio, (Eds.) *Giambattista Venturi. Scienziato, Ingegnere, Intellettuale fra età dei Lumi e Classicismo* (Olschki, Florence, 2005).
19 Ref 9, p. 389.
20 Ref 9, p. 386.
21 Lord Rayleigh, "Our perception of the direction of a source of sound," Nature **7**, 32-33 (1876).
22 B. Bowers, *Sir Charles Wheatstone F.R.S. 1802-1875* (Her Majesty's Stationery Office, London, 1975).
23 N. J. Wade, "Charles Wheatstone (1802-1875)," Perception **31**, 265-272 (2002).
24 N. J. Wade, "Philosophical instruments and toys: Optical devices extending the art of seeing," J. of the History of the Neurosciences **13**, 102-124 (2004).
25 N. J. Wade, "Sound and sight: acoustic figures and visual phenomena," Perception **34**, 1275-1290 (2005).
26 C. Wheatstone, "Contributions to the physiology of vision - Part the first. On some remarkable, and hitherto unobserved, phenomena of binocular vision," Philosophical Transactions of the Royal Society **128**, 371-394 (1838).
27 C. Wheatstone, "Experiments on audition," Quarterly J. of Science, Literature and Art **24**, 67-72 (1827).
28 Ref 27, p. 69.
29 Ref 27, p. 71.
30 H. E. Ross, and D. J. Murray, *E. H. Weber: The Sense of Touch* (Academic Press, London, 1978). Weber's two monographs on the sense of touch, the first in Latin and the second in German, are translated in this book.
31 E. H. Weber, and W. Weber, *Wellenlehre, auf Experimente gegründet, oder über die Wellen tropfbarer Flüssigkeiten, mit Anwendung auf die Schall- und Lichtwellen* (Gerhard Fleischer, Leipzig, 1825).
32 H. Dove, "Über die Combination der Eindrücke beider Ohren und beider Augen zu einem Eindruck," Monatsberichte der Berliner preussische Akademie der Wissenschaften **41**, 251-252 (1841).
33 Ref 30, p. 147.
34 A. Seebeck, "Beiträge zur Physiologie des Gehör- und Gesichtssinnes," Annalen der Physik und Chemie **68**, 449-465 (1846).
35 G. T. Fechner, *Über einige Verhältnisse des binocularen Sehens* (Hirzel, Leipzig, 1860).
36 J. E. Kunke, *Gustav Theodor Fechner (Dr. Mises). Ein deutsches Gelehrtenleben* (Breitkopf & Härtel, Leipzig, 1892).
37 Ref 12, pp. 197-198.
38 R. T. H. Laennec, *Traité de l'Auscultation Médiate* (Chaudé, Paris, 1819).
39 N. Comins, "New stethoscope," London Medical Gazette **4**, 427-430 (1829). p. 430.
40 Ref 12, p. 197.
41 Ref 12, p. 201.
42 Ref 12, pp. 196-197.
43 Ref 12, p. 204.
44 Ref 12, p. 205.
45 Ref 12, p. 205.
46 S. S. Alison, "The physical examination of the chest in pulmonary consumption and its intercurrent diseases," British and Foreign Medico-Chirurgical Review **28**, 145-154 (1861).
47 S. P. Thompson, "On binaural beats," London, Edinburgh, and Dublin Philosophical Magazine and J. of Science **4**, 274-276 (1877).
48 S. P. Thompson, "Phenomena of binaural audition," London, Edinburgh, and Dublin Philosophical Magazine and J. of Science 6, 383-391 (1878).
49 S. P. Thompson, "The pseudophone," London, Edinburgh, and Dublin Philosophical Magazine and J. of Science **8**, 385-390 (1879).
50 C. Wheatstone, "Contributions to the physiology of vision – Part the second. On some remarkable, and hitherto unobserved, phenomena of binocular vision," Philosophical Transactions of the Royal Society **142**, 1-17 (1852).
51 Ref 49, p. 385.
52 Ref 49, p. 387.
53 A. Steinhauser, *Die Theorie des binaurealen Hörens. Ein Beitrag zur Lehre vom Schalle* (Gerold, Vienna, 1877).
54 A. Steinhauser, "The theory of binaural audition. A contribution to the theory of sound," London, Edinburgh, and Dublin Philosophical Magazine and J. of Science **7**, 181-182 (1879).
55 S. P. Thompson, "On the function of two ears in the perception of space," London, Edinburgh, and Dublin Philosophical Magazine and J. of Science **13**, 406-416 (1882).
56 Lord Rayleigh, "On our perception of the direction of a source of sound," London, Edinburgh, and Dublin Philosophical Magazine and J. of Science **13**, 214–323 (1907).
57 C. Stumpf, "Binaurale Tonmischung, Mehrheitsschwelle und Mitteltonbildung," Zeitschrift für Psychologie **75**, 330-350 (1916).
58 R. M. Stern, G. J. Brown, and D-L. Wang, "Binaural sound localization", in *Computational Auditory Scene Analysis*, edited by D-L. Wang, and G.J. Brown (Wiley, Hoboken, NJ, 2005), pp. 147-186.

59 R. H. Domnitz and H. S. Colburn, "Lateral position and interaural discrimination," J. Acoust. Soc. Am. **61**, 1586–1598 (1977).

60 R. M. Hershkowitz and N. I. Durlach. "Interaural time and amplitude jnds for a 500-hz tone," J. Acoust. Soc. Am. **46**, 1464–1467 (1969).

61 J. Blauert. *Spatial Hearing* (revised edition) (MIT Press, Cambridge, MA, 1997).

62 F. L. Wightman and D. J. Kistler. "Headphone simulation of free-field listening. I: Stimulus synthesis," J. Acoust. Soc. Am. **85**, 858–867 (1989).

63 F. L.Wightman and D. J. Kistler, "Headphone simulation of free-field listening. II: Psychophysical validation," J. Acoust. Soc. Am. **85**, 868–878 (1989).

64 D. Deutsch, "Binaural integration of melodic patterns," Perception & Psychophysics **25**, 399-405 (1979).

65 A. S. Bregman, *Auditory Scene Analysis* (MIT Press, Cambridge, MA, 1990).

66 E. C. Cherry and W. K. Taylor, "Some further experiments upon the recognition of speech, with one and with two ears," J. Acoust. Soc. Am. **26**, 554-559 (1954).

67 E. D. Schubert, and C. D. Parker, "Addition to Cherry's findings on switching speech between two ears," J. Acoust. Soc. Am. **27**, 792-794 (1956).

68 S. Axelrod, L. T. Guzy, and I. T. Diamond, "Perceived rate of monotically and dichotically alternating clicks," J. Acoust. Soc. Am. **43**, 51-55 (1968).

69 C. J. Darwin and R. P. Carlyon, "Auditory grouping," in *Hearing* edited by B. C. J. Moore (Academic Press, San Diego, 1995), pp. 387-424.

70 A. J. M. Houtsma and J. L. Goldstein, "The central origin of the pitch of complex tones: Evidence from musical interval recognition," J. Acoust. Soc. Am. **51**, 520-529 (1972).

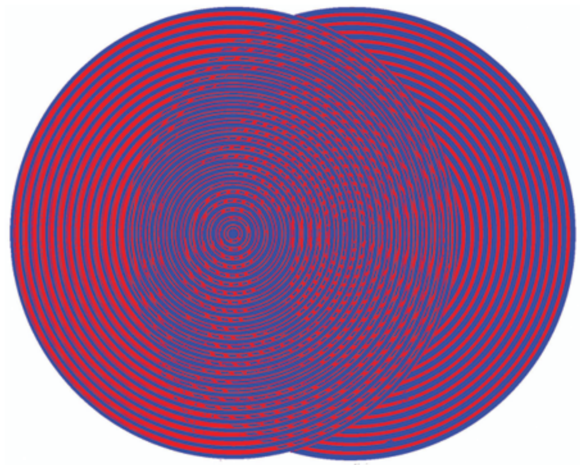
71 J. G. Beerends and A. J. M. Houtsma, "Pitch identification of simultaneous dichotic two-tone complexes," J. Acoust. Soc. Am. **85**, 813-819 (1989).

72 C. J. Darwin and V. Ciocca, "Grouping in pitch perception: Effects of onset asynchrony and ear of presentation of a mistuned component," J. Acoust. Soc. Am. **91**, 3381-3390 (1992).

73 R. Efron and E. W. Yund, "Dichotic competition of simultaneous tone bursts of different frequency – III. The effect of stimulus parameters on suppression and ear dominance functions," Neuropsychologia **13**, 151-156 (1975).

74 D. Deutsch, "Ear dominance and sequential interactions," J. Acoust. Soc. Am. **67**, 220-228 (1980).

75 J. V. Tobias, "Application of a "relative" procedure to a problem in binaural-beat perception," J. Acoust. Soc. Am. **35**, 1442-1447 (1963).



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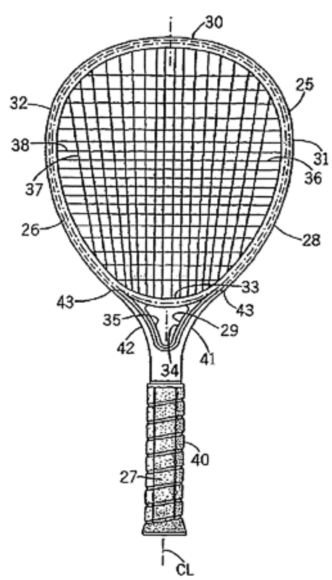

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43.40.Tm GAME RACQUET WITH SEPARATE HEAD AND HANDLE PORTIONS FOR REDUCING VIBRATION

William D. Severa *et al.*, assignors to Wilson Sporting Goods Company
20 November 2007 (Class 473/536); filed 6 January 2005

*Shock on a typical tennis racquet can last about 5 ms and vibration can last about 1000 ms after ball impact. This can cause physical problems such as tendonitis, or tennis elbow. A vibration absorbing material **66**, which can be urethane, natural rubber, butyl rubber, or synthetic rubber, is placed between the handle portion **46** and the head portion **45** of racquet **44**.—Neil A. Shaw*