WE live in a three-dimensional world. We have an intuitive sense of space which enables us to perceive and understand the spatial relations between the material objects of our universe. The sensations which we receive from our eyes and ears originate from wavefronts existing in three dimensions. These two important senses have developed differently in response to the two types of radiation. Light consists of electromagnetic waves, whilst sound is made up of pressure waves in a material medium which is usually air. Our ears and eyes are able to perceive the spatial characteristics of sound and light waves, but they do so in different ways.

It is apparent that the ability of our ears and eyes to perceive these relationships is related to our having two of each type of sense organ. Let us examine first, however, the characteristics of individual eyes and ears. The single eye receives light waves in the form of a two-dimensional scene on the retina; it can deduce spatial relationships properly only in the two dimensions of this plane. The single ear receives a sound wave as one time-varying stream of pressure variations through a single channel; from this 'zero dimensional' stream it cannot deduce any spatial relations. It may be argued that even a single ear can tell the relative distance of, say, an approaching car, but in doing so the brain has to make certain assumptions about the constancy of the sound source intensity and other factors. Likewise with the eye, which must draw on visual memory of perspective to perceive 'depth'. We may therefore say that the single eye is basically a two-dimensional receptor and the single ear a zero dimensional receptor.

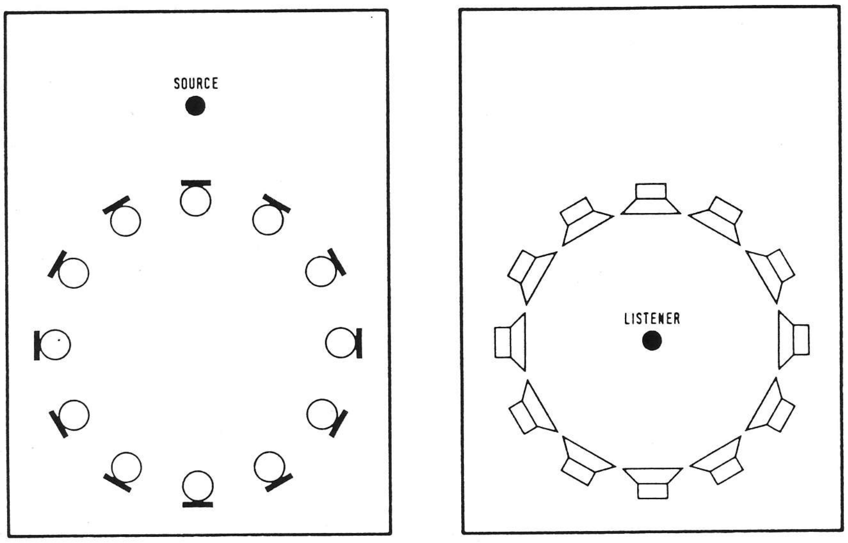
When *two* eyes and ears are considered, we find that the capacity for spatial perception is enhanced. With two eyes, characteristics of the third dimension which were not very apparent to the single eye become obvious. Thus two organs which were separately two-dimensional receptors become three-dimensional receptors when used together. We note that in order to perceive the third dimension, nature has set the two eyes along the left–right direction and not along the front–back or above–below directions. Similarly, the two ears are positioned on the left and right as well. Because of this positioning, they are able to perceive spatial relationships in the left–right direction. Thus the two ears which were separately zero-dimensional receptors become one-dimensional receptors when used together. This is deduced by considering the relative amplitudes and arrival times of sounds at the left and right ears. If they were purely single channel receivers of sound pressures, then it would seem that they can perceive only the left–right direction. However, we know from experience that we can certainly perceive sounds as coming from the back as distinct from the front, and also from above and below. Other factors will have to be brought in to explain this ability; this will be discussed later. Comparing the eyes and the ears, we note that both of these pairs of organs are able to reconstruct an extra dimension as compared with their lone versions; furthermore, the eye as a spatial receptor is two dimensions better off than the ear.

Though we live in a three-dimensional world, our sense organs have developed to place more emphasis on some directions than on others. Being bound to the surface of the Earth by gravity we find that we move approximately in a two-dimensional space determined by that surface. Hence the above–below dimension has less importance for us (unless, perhaps, we happen to be airplane pilots). In the front–back direction, we place more importance on the front than the back since we walk in a forwards direction; hence our eyes are placed in the frontal direction in relation to our usual direction of motion. In the left–right direction, we find that we have no preference for one or the other, and it is equally important to know what is on the left as well as on the right side.

Our eyes and ears have developed to reflect these relative importances of different dimensions. The eyes have developed further away from omnidirectionality than the ears. Our field of vision is relatively limited in the above and below directions and totally absent in the backward direction; it is to the left and right that we have the widest range of vision. The ears are much less severely restricted in their directionality and are still reasonably omnidirectional. However, their placing on the left and right sides ensures that they are best suited for the perception of left–right directions. The shape of the pinnae (external ears) also seems to indicate a preference in favour of the front. Thus the ears would seem also to have the same bias towards the left–right dimension and the front rather than the back as for the eyes, though to a lesser degree. In practice, we can perceive sounds coming from every direction, though less accurately than the eye is able to do within its more restricted field. In stereophonic sound reproduction, it seems entirely natural that we should employ two loudspeakers placed in front of us on the left and right sides; this reflects a natural bias towards directions which are emphasised by the eyes and ears.

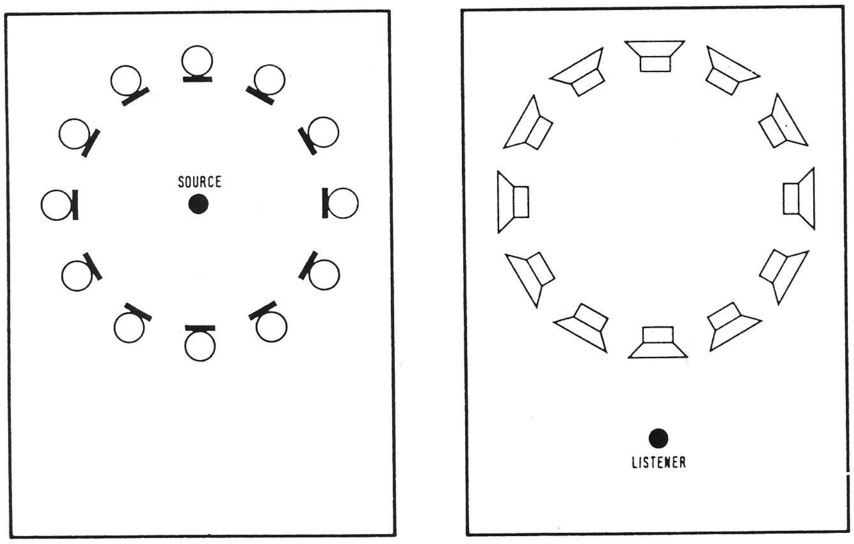
In stereophony, the object is to reproduce the left–right dimension that the two ears themselves are able to perceive because of their

FIG. 1 THE SOUND-FIELD SYSTEM



RECORDING ROOM ACOUSTICALLY LIVE — LISTENING ROOM ACOUSTICALLY DEAD

FIG. 2 THE SOUND-SOURCE SYSTEM



RECORDING ROOM ACOUSTICALLY DEAD — LISTENING ROOM ACOUSTICALLY LIVE

sound in SPACE

SPATIAL ASPECTS OF SOUND REPRODUCTION—THE ALTERNATIVES FOR DOMESTIC USE

By B. T. G. TAN*

position on the left and right sides. We place the loudspeakers in front of us purely because we give greater importance to the frontal direction than to the back. Similarly, stereoscopic photography is able to reproduce the depth dimension by presenting a pair of slightly different two-dimensional pictures to the two eyes. However, the analogy between stereophonic sound and stereoscopic photography (or cinematography) is not quite exact. In stereoscopy, the two scenes are presented so that each eye sees only the one that is intended for it; there is complete separation of pictures intended for the two eyes. In stereophony, the sound from each loudspeaker is perceived by *both* ears, and the stereophonic effect depends on amplitude, spectrum and time differences between the sound waves received by the two ears.[1] These amplitude and 'phase' effects may be reconstructed by intensity differences from the two speakers, such as are obtained by a coincident crossed stereo pair of microphones. A closer analogy to stereoscopic photography would be binaural sound reproduction through headphones, where the two ears have their own completely separate channels. Binaural reproduction, like conventional stereophonic sound, reconstructs the left–right spatial relationships, but without giving more prominence to the front than to the back direction. Efforts have been made to use a stereophonically recorded signal in a binaural fashion, through headphones. The intended effect is to reproduce the sensation of listening to a stereophonic pair of loudspeakers through headphones.[2]

Recently, much interest has been generated in the spatial aspects of sound reproduction, in particular by four-channel stereo and also by omnidirectional speakers such as the Bose 901. If the ear were only responsive to left–right spatial effects, then two-channel stereophonic sound would be the ultimate in sound reproduction. However, the ears are in practice also able to distinguish front–back and above–below spatial effects, i.e., they are omnidirectional. Hence the reproduction of sound taking these other directions into account is necessary for a more accurate rendering of the original. Let us by-pass for the present the mechanism by which the ear is able to perceive these other directions, and simply assume that it is able to do so.

When stereophony was first introduced, it was often demonstrated with a host of 'gimmicky' effects like trains and tennis matches. However, the true worth of stereo has been shown to lie in its ability to reproduce recorded music more closely to the original, with correct left–right spatial relationships and a correspondingly improved sense of 'depth', computed by our ears from stereophonically reproduced ambience within the forward 'sound-stage'. In the same way, the introduction of four-channel stereo or 'quadraphonic' sound has been marked by numerous demonstrations of spectacular sound effects such as motorcycles roaring around the listener or brass bands from four corners of the room. Eventually, the true value of quadraphonic sound will probably be shown to lie in its ability to reproduce recorded music more satisfyingly than ordinary stereophonic sound does at present. In particular, more correct reproduction of room acoustics and reverberation has been shown to enhance even further the enjoyment of recorded music.

Concentrating on the reproduction of room acoustics, we shall consider the problem of the spatial aspects of sound reproduction in a general way and then make particular reference to quadraphonic sound. Apart from quadraphony, there are other approaches now appearing which attempt to give better spatial effects, like the omnidirectional loudspeakers mentioned previously. These attempts may be divided into two basic groups with two quite different aims. We will ignore the vertical dimension for the moment and consider the spatial aspects in the horizontal plane only, since the vertical, or above–below dimension has less importance than the others.

The first group of approaches to spatial reproduction has as its objective re-creation of the original sound-field as perceived by a listener who would have been in the recording room with the sound-source. Thus we would wish to reproduce not only the sound coming from the source or sources, but also the reverberations which occur in the recording room due to the room surfaces. This may be accomplished by surrounding the position of the listener in the recording room with a ring of microphones facing outwards, which are more or less directional enough so that their individual fields just overlap. These microphones would 'intercept' all the sound waves which would have reached the listener from all directions. The reproduction of the recorded channels from these microphones is then played back in the listening room through a ring of loudspeakers facing inwards and surrounding the listener. Each speaker plays back the sound recorded by the corresponding microphone in the recording ring which was facing outwards (**fig. 1**). The loudspeakers should be as directional as the microphones to form a continuous sound-field. Since the object is to reproduce the sound-field of the recording room as closely as possible, the listening room should not add any reverberations or reflections to the reproduced sound; in other words it should be acoustically 'dead'. There is of course no reason in particular why we should make the microphones and loudspeakers in the shape of a circle, except that it is the simplest. Any shape should suffice, provided that both microphones and loudspeakers are in the same configuration. Also, since we are attempting to reproduce the original sound-field, the more microphones and loudspeakers we use, the more accurate the reproduction will be. Let us call this system the *sound-field system.*

The second group of approaches has a different objective; to re-create the sound-source (or sources) in the listening room as accurately as possible. Here the intention is to exploit the reverberation characteristics of the *listening room*, not the recording room. If we consider again a sound-source in the recording room, we can attempt to accomplish this by surrounding the source with a ring of microphones facing inwards towards the source, rather than outwards as in the sound-field system. We wish to record the sound source as closely as possible without reverberation added from the recording room, so that in this case the recording room should be acoustically dead. For playback, a ring of loudspeakers is used in the listening room with the channel from each microphone played back through the correspondingly positioned loudspeaker. The speakers will thus play back the sound radiated by the source which was intercepted by the microphones; in this way the sound-source is reproduced as though it were in the listening room (**fig. 2**). Again, we assume that the microphones and loudspeakers are directional enough so that their individual fields just overlap. The sound waves from the loudspeakers will then produce reverberation effects from the surfaces of the listening room, just as if the source itself were there. Thus the listening room should not be dead, since we are using its reverberation characteristics. Let us call this arrangement the *sound-source system.*

In both the sound-field and the sound-source systems, we are trying to utilise reverberation to give a better spatial effect in the reproduction. However, the aims and techniques of both systems are quite different and may be said to be complementary. In the sound-field system, the microphones and loudspeakers surround the listening position, while in the sound-source system they surround the source of sound. Furthermore, for the sound-field system the microphones face outwards and the loudspeakers face inwards, while in the sound-source system the reverse is true. The conditions for room acoustics are also opposite: in the sound-field system the recording room is live, i.e., reverberant, while the listening room must be dead, and for the sound-source system the reverse is true. Hence we see that though the technique and objectives of the two systems are quite different, they are actually complementary to one another. Both systems have as their common objective the reproduction of sound with its spatial characteristics.

Which one is more suitable or more desirable? The answer to this must depend on the

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circumstances. One system will be more appropriate than the other if we are trying to reproduce a particular type of ensemble in a particular type of recording room. For example, let us say that we wish to record a symphony orchestra in a large concert hall and reproduce the recording in a domestic living room. In this case, the sound-field system would be more appropriate since it would be desirable to record the orchestra and the reverberations resulting from the acoustics of the hall. In other words, we wish to be transported to the concert hall. We thus require the living room to be as acoustically dead as possible, which may be accomplished by carpets, curtains and other furnishings. If we tried to use the sound-source system, we would be attempting to transport the orchestra to the living room, which is less desirable from the acoustical point of view. The sound-field system is used whenever we want to reproduce the acoustics of the recording room.

A completely different set of circumstances would be met if, say, we wished to record a small ensemble or a soloist and play back the recording in a large auditorium. This time, we may desire to utilise the acoustics of the listening room, especially if the recording is made in a much smaller room with less impressive acoustics. In such a case we might choose to use the sound-source system, and try to reproduce acoustically the soloist in the auditorium, so that the recording when played back would sound as if the soloist were in the auditorium, with reverberations just as they would be from the soloist 'live'. Thus the recording room would have to be acoustically dead, so that it added nothing in terms of reverberation to the recording. Of course, we could have chosen just as well to reproduce the soloist by the sound-field system; but this would be less practicable because it would mean rendering a large auditorium acoustically dead. Also, if the soloist or ensemble were recorded in a small room, it might sound inappropriate if the recording attempted to reproduce the small room's acoustics in a large auditorium. Thus the sound-source system may be considered more appropriate in this case.

We have so far considered the two systems as attempting to reproduce the spatial effects only in two dimensions, i.e., the horizontal plane. If we were to extend the two cases to three dimensions, then we find that the rings of microphones and loudspeakers become spheres. In the sound-field system the sphere surrounds the listening position, while in the sound-source system it surrounds the source. The ultimate would not be to have a large number of microphones and loudspeakers positioned on the surface of the spheres, but to be able to record and reproduce the sound wavefronts by some kind of acoustical membrane on the surface of an expandable/contractable sphere, which would first record the sound wavefronts over the surface continuously, and then reproduce the sound wavefronts also continuously. In practice we have to be content with reproducing the wavefronts with a finite number of microphones and loudspeakers.

Which of the two systems would be more appropriate for wide domestic use? It seems that the sound-field system is more relevant, since in most cases the reproduction is played back in a domestic living room of small or moderate dimensions. Also, we usually desire to reproduce the acoustics of the concert halls in which recordings take place, for which the sound-field system would be more appropriate.

FIG. 3 STEREOPHONIC LOUDSPEAKER PLACEMENT

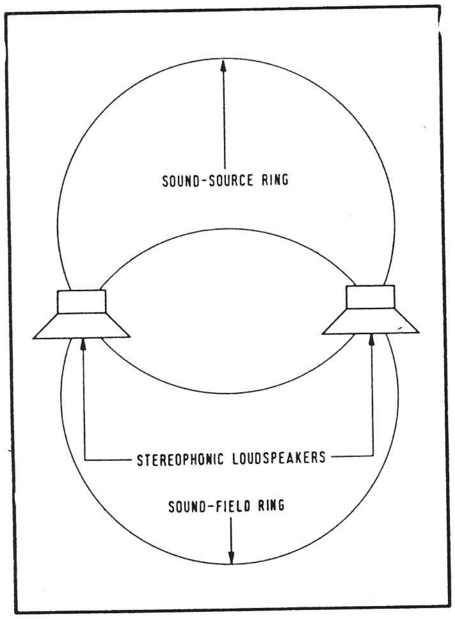
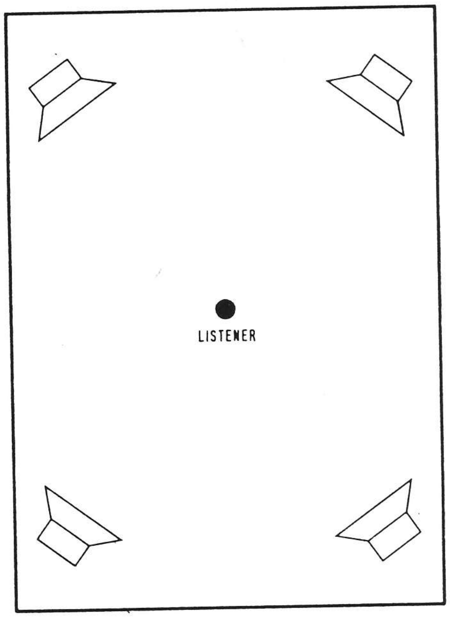


FIG. 4 QUADRAPHONIC SOUND



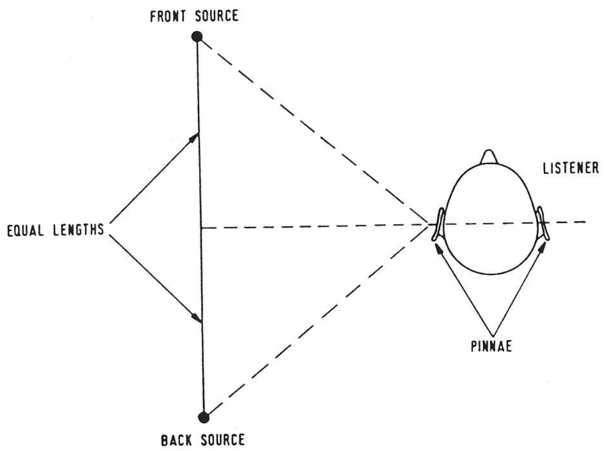


FIG. 5
RECEPTION OF SOUND BY THE PINNAE

However, if we are trying to reproduce soloists or small ensembles, the sound-source system may be preferable in order to give the impression of the soloist or ensemble situated in the living room.

Perhaps we can summarise the difference between the two systems by saying that the sound-field system transports the listener (in his living room) to the concert hall, while the sound-source system transports the performers from the concert hall to the living room. Most people would probably choose to be transported to the concert hall to experience the hall acoustics as well, so that the sound-field system is the better one for application to domestic purposes. Let us call the fully three-dimensional sound-field system with microphones and loudspeakers arranged in spheres the *omniphonic system*; in this system the complete sound-field is reproduced and envelopes the listener.

How are the sound-field and sound-source systems related to conventional stereophonic sound and the new quadraphony, as well as to omnidirectional loudspeaker systems? If we take the two rings of the sound-field and sound-source systems and overlap them, we get two intersecting points. Each point marks a position where two loudspeakers of the two systems may coincide; we may consider the speakers at these two positions to be our normal stereophonic pair (**fig. 3**). Is stereophonic reproduction related to the sound-field or sound-source systems? In other words, are we trying in stereophonic reproduction to reproduce the recording studio acoustics or to transport musicians to the living room? This cannot be answered definitely since the stereophonic pair of loudspeakers cannot by themselves define the rings of the sound-field or sound-source systems. Some present-day stereophonic 'pop' recordings are made in dead surroundings, though most music is recorded in a fairly live studio with some ambient information, which corresponds to the sound-field system and is thus more appropriate to domestic surroundings. If the loudspeakers are angled inwards toward the listener, we may consider them to be part of an imaginery sound-field ring of speakers facing inwards, whilst if they angled outwards (which is far less common a practice) they may be considered part of a sound-source ring. The positioning of the loudspeakers in a forward direction without any angling makes them 'neutral' with respect to either system.

Quadraphonic sound reproduction is obviously related to the sound-field system, since the loudspeakers surround the listener. The four speakers of the quadraphonic system may be considered to be part of the inward facing ring of the sound-field system, since they face towards the listener (**fig. 4**). The trend towards quadraphonics would confirm that the sound-field system is more desirable for general domestic use.

On the other hand, omnidirectional loudspeaker systems are approximations to the sound-source system. This is so because, for one thing, they make use of listening room acoustics in order to be effective. In the Bose speakers, for example, reflections from the front wall of the listening room are used, just as in the sound-source system with its ring of outward facing loudspeakers. However, the Bose system may be regarded as a closer approximation to a true sound-source system by making the assumption that the sound coming from the back of the source is the same as that coming from the front of the source directly towards the listener, and so does not need separate microphones. Also, the spreading out of sound by an omnidirectional stereo pair attempts to exploit listening room acoustics as in the sound-source system. However in practice the simulation of a true sound-source system is so poor that, even for a fixed central listener, some loss of definition of the stereophonic image tends to occur.[3]

A better approximation to the sound-source system might use four microphones as in the quadraphonic arrangement, but placed surrounding the sound source, with the four loudspeakers facing outwards towards the room walls. In any case, except for the smallest sound sources, a sound-source type system would be inappropriate for the small acoustics of a domestic listening room.

The Bose, Sonab and other omnidirectional systems are thus really attempts to reproduce a sound-source system with just two channels, and somewhat analogous to attempts to reproduce a quadraphonic system with two channels. These attempts fall into two classes: the first aims to reproduce accurately the four separate quadraphonic channels, with various means of coding to squeeze them into two normal stereophonic channels; the second attempts to synthesize an approximation of quadraphonic sound by processing the two stereophonic channels to give four channels which are not totally independent. Into this second group fall systems like the Sansui QS-1 Quadphonic Synthesizer and other four-from-two channel systems.[4,5]

One question that emerges is: which will become the most common and standard system? Going back to the question of spatial reproduction in three dimensions, perhaps we can try to give priorities to each of the three dimensions in order of importance. The vertical (above–below) dimension is the least important, followed by the front–back dimension, while the left–right dimension is the most important. Hence in the spatial reproduction of sound, the stereophonic left–right loudspeaker pair is the most important. Since the front–back dimension is less important, we may eventually be content with something less than full quadraphonic sound, settling for one of the four-from-two channel systems. The front direction will remain more important than the back direction, so that the main sound channels will still be the two at the front, with the rear channels obtained from them by some sort of processing. We may never find it necessary to reproduce the vertical dimension at all, so let us hope that no new systems will be suggested for this purpose. However, if they ever are, then another four speakers lying above the four of quadraphonic sound in a plane above the listener may be necessary(!); if such a thing ever comes about, the least of our worries may be to suggest a name for it—perhaps octaphonic sound may be suitable.

However, in the reproduction of spatial effects using more than two loudspeakers it may be possible to use fewer speakers than might seem necessary initially. In stereophonic sound, two loudspeakers are used to reproduce one dimension (plus some depth). To reproduce two dimensions in the horizontal plane, perhaps only three loudspeakers may be necessary since a plane is defined by three points. Similarly, four loudspeakers could be used to reproduce all three dimensions since four points are the minimum needed to define a three-dimensional space.[6] This would be more economical than using eight speakers—i.e., two quadraphonic systems—to give the vertical dimension, but would probably be in practice less effective in giving well-defined directional information. As an analogy, we note that in theory only two speakers are necessary for one-dimensional stereophony, but because of effects like the hole-in-the middle and off-axis loss of definition, three or more speakers (for example, five in some large screen cinema systems) can give more effective stereophonic effects for a large audience. This all depends on the mechanisms by which the ear synthesises directions; but we will not go into this any further since it probably requires lengthy analysis and much experiment.

We have considered loudspeaker systems at some length; let us now turn our attention to systems in which headphones are used to reproduce spatial and directional effects. All headphone systems have two channels, one each for the left and right ears. A pair of headphones will in effect screen the listener acoustically from the listening room; furthermore, the cavity formed by the headphones and the head was virtually no 'room' acoustics to speak of. Hence the purpose of a headphone system with respect to spatial effects *must* be to reproduce the reverberations of the recording room which is the same as the objective of the sound-field system. The difference is that the headphone system recreates the field perceived by the ears at each individual ear, whereas in a sound-field system with loudspeakers the ears are placed in the same sound environment as that in the recording room, and ideally should be able to move about freely in this environment.

The most common method of using headphones is simply to feed the two channels of a stereophonically recorded signal (meant for two loudspeakers) into the left and right sides of the headphones. A true binaural system would be more accurate, recording the two channels from two microphones placed on either side of a dummy head, where the ears are positioned. The microphones may be slightly angled forward to bias the signal in favour of the front direction, since the ears do give this slight bias by using the pinnae. The recorded signals when played back through a pair of headphones would present to the ears a closer representation of what they would have received in the recording room than a normal stereophonic signal. Such a system would be capable of recording only left–right spatial information. We have assumed the ears to be simple point receptors, capable of receiving only zero-dimensional signals; the two channels of a binaural system should thus reproduce for the two ears only the left–right directional effects, since the binaural microphones would not be able to separate the sounds coming from the front from those coming from the back. How would it be possible for a headphone system to reproduce spatial information from the other two dimensions also?

The most obvious method would be for the headphones themselves to incorporate more than one sound radiator channel in each side to reproduce the directional effects of the received sound-field. Taking a quadraphonic system, for example, each side would incorporate two speakers, one in front of and the other behind the ear. This headphone four-channel system, which has in fact already been designed and manufactured,[7] should not be fed the four channels of a quadraphonic system directly, if spatial accuracy is desired. Feeding the four channels of this system directly with the four signals of a quadraphonic source would be analogous to feeding a pair of conventional headphones directly with the two channels of a normal stereophonic system. It is possible to process the two stereophonic channels in order to 'correct' them for binaural listening, as mentioned earlier,[2] though in this case the differences are not generally remarkable.

The four quadraphonic channels may be processed in a similar way to give the effect of listening to the sound-field from four quadraphonic loudspeakers. Each processed channel fed to a headphone radiator would be obtained by mixing the original four channels in suitable proportions. This could be done by recording the sound-field from the four speakers at a dummy head in the listening position with four microphones positioned where the headphone radiators would be for playback. If the mixing proportions could be determined, this processing may be done by electronic filter circuits, as it is done for binaural processing of a stereophonic signal.

Of course, if the recording is intended *solely* for headphone listening, then it could be done with the four microphones positioned on the dummy head directly, as in true binaural recording. Extending this idea, we could use more than two microphones and radiators per ear in order to reproduce the sound-field at the ears more accurately, in order to reproduce the spatial effects. However, since we have only two ears, it would be a more elegant solution if we could obtain the full three-dimensional spatial effects with only two sound channels, one to each ear. After all, the ear is able to perceive these effects with only two zero-dimensional sound channels received via the auditory canal and passed into the auditory nerve, one for each ear. In simple theory, the two ears, if they are considered as single channel receptors, together should be able to perceive only the left–right directional effects. In practice we know they can do much more than this; how is this achieved?

One possible answer is that in trying to locate the direction of a sound-source, other than in the left–right direction, we employ small head movements in order to vary the relative loudness and phase of the sounds received by the two ears. Since in order to employ this method there must be relative movement between the head and the sound-field, we can see that it will be difficult to apply it to a headphone system. The headphones will in effect make this relative motion impossible, unless we can devise a way of suspending the headphones on the head to allow relative motion, which will probably be a highly complex engineering problem.

Another possible answer, conjectural at this stage, is that the pinnae play some part in helping this determination of direction in the front–back and above–below planes.[8] The pinnae have been thought to be purely vestigial sound focusing appendages; they may, in fact do more than just collect sound waves. The shape of the pinnae is quite asymmetrical with respect to the front–back and above–below directions. Taking the front–back direction, it is apparent that the pinnae are more favourable to the front; hence a sound coming from a point behind the head is treated differently from a sound coming from a point in front, at the same distance and also equidistant from the left–right axis passing through the head (**fig. 5**). This different treatment may result in the back sound being weaker than the front; in this respect the effect of diffraction and absorption by the head may also cause intensity differences between sounds coming from the front and rear. Furthermore, as well as intensity differences, each pinna may process the sounds from the front and back differently. Before entering the ear, the sound wave may be diffracted and reflected from the surfaces of the pinnae so that waves from the back eventually reach the ear canal in a different form from identical sounds coming from the front.

What the nature of this processing may be is a matter for experimental work to decide. However, the differences introduced by the pinnae must reach the auditory canal as time varying differences, since we have postulated that the auditory canal enables only a single time-varying pressure wave to be transmitted. Thus we may say that the pinnae enable the front and rear sounds to be distinguished by a time-domain analysis. We may extend this hypothesis to the above-and-below directions, since the pinnae are also asymmetrical in that plane. If this is true, then the pinnae may be said to perform this analysis on all sounds received from three dimensions in order to determine their direction of incidence. However, the left–right direction perception is still mainly achieved by the intensity and time differences received by the two ears together.

If this hypothesis is anywhere near the truth, we may be able to reproduce full three-dimensional spatial effects with only two channels through headphones. We may use a dummy head with artificial pinnae; these should be constructed to have the same acoustical characteristics as real pinnae on a human head. The two microphones would be located in the same positions as the opening of the auditory canals as so to record the sounds going into the canals after processing by the pinnae. The surface area of the microphones should be as small as the opening of the auditory canals for the best effect and also be omnidirectional, since they will have to collect sound waves from the surfaces of the pinnae immediately adjacent to them. In reproduction, the two recorded channels should be played back, not through conventional headphones but through earpieces positioned directly at the opening of the auditory canals, past the pinnae, so that the canals will receive sound which will appear to have been processed by the listener's own pinnae.

If the hypothesis is correct, the ear and the brain will interpret the sounds received as having been processed by its own pinnae and thus experience the full three-dimensional spatial effects, since the brain would be able to decode the processing put in by the pinnae as spatial information. In fact, the effect should be similar to that from omniphonic reproduction as we have defined it earlier. The only difference is that in this system, which we may term *omniaural* reproduction (or true binaural reproduction), a specific 'point of view' of the sound-field as perceived by a particular listener (in this case the dummy head) is reproduced; we cannot obtain a change in the perceived field by moving our heads. In omniphonic reproduction, the listener is in the complete reproduced sound-field and can thus experience a difference by moving his head.

In order to make these various differences clearer, we may bring in some comparisons with visual effects. It was mentioned that binaural reproduction was analogous to stereoscopic photography. Omniaural reproduction is an even closer analogy—exactly analogous in fact, since it reproduces the three-dimensional sound effects exactly. In omniaural reproduction, separate channels are presented to each ear, just as separate pictures are presented to each eye in a stereoscopic photograph. Furthermore, in both systems specific points of view are presented which cannot be altered by movement of the head. In stereoscopic photography, parallax effects are not possible; similarly, in omniaural reproduction, aural parallax effects would not occur. Omniphonic reproduction has a close visual parallel in optical holography. In holography, an actual wavefront as would be perceived by an observer is reproduced; parallax effects can be observed by moving the head. Similarly, in omniphonic reproduction we can by moving the head experience exactly the same effects that we would experience in the original recording room.

If the theory of the pinnae is correct and omniaural sound does work, then it would be interesting to try processing the four channels of quadraphonic sound into two pinnae-processed channels so that by headphone (or rather earphone) reproduction we could experience front–back as well as left–right directional effects from two earphone channels. The simplest way would be to record the sound coming from four quadraphonic loudspeakers through two omniaural microphones in a dummy head with pinnae. However, if we were ever able to process sound electronically in the same way as the pinnae, then two channels may be obtained from four by means of circuits; each resultant channel would be a mixture of the original four and would also be processed as though by a pinna. This is analogous to the electronic processing of stereophonic sound binaurally. We may call the result *quadraural* sound.

It is interesting to observe the improvement in reproduction in the sound channels of television and video recording systems. For black-and-white video, monophonic sound was the standard. With the new videocassettes and EVR, which will be in colour, the standard being adopted for the sound channels seems to be stereophonic, which is a good sign that more attention is being paid to the sound aspect of entertainment. If video recording and display ever progress further to give widescreen and three-dimensional effects, then it would be safe to assume that the sound channels would be at least quadraphonic.

The subject of the reproduction of the spatial characteristics of sound has been examined from various viewpoints, and some hypotheses and theories have been suggested. Interesting as the discussion of these topics may be, the final arbiter of any new developments in sound must be, as always, actual listening and not simply theoretical speculation and conjectures. It is hoped that there will be more fruitful experimentation in this direction.

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