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THE ROLE OF HEAD MOVEMENTS AND VESTIBULAR AND VISUAL CUES IN SOUND LOCALIZATION[1]

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In a previous paper[2] the writer has demonstrated that a distinct localization of sound exists for directions which do not fall into the horizontal plane but lie above or below at varying elevations, in other words that a discrimination of directions with respect to above and below and front and back is possible as well as discrimination with respect to right and left which has been studied for many years. It was found that only a head movement during the presentation of the sound affords an adequate discrimination of sound direction in the dimension of above and below and thus makes localization complete. This is probably the reason why sound localization with respect to above and below has not been demonstrated in the laboratory at an earlier time. The paper referred to gives an analysis of the manner in which a complete perception of a sound direction is achieved with the help of a head movement. The binaural cues on which sound localiza-

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[2] Ueber die Wahrnehmung der Schallrichtung. *Psychol. Forsch.*, 22, pp. 238–266 (I). A short English report on the same work has been published in the *J. Acoust. Soc. Amer.*, 1939, pp. 270–74 (II). The two papers will be referred to as I and II respectively. In the present paper the writer has attempted to present the material in such a way that it can be understood without knowledge of the previous papers. While paper II lacks theoretical discussion it may be useful for a quick reference to previous experimental results.

tion is primarily based do not suffice to characterize a sound direction completely. Yet, during a head movement the binaural cues as produced by the sound direction are altered, and the particular form of this change can in each case strictly determine the given sound direction. This is thoroughly discussed in the article mentioned. Experiments are reported in which perceived sound directions were synthetically produced in accordance with the head movement principle, which was thus verified. It is obvious that the change which the primary factors undergo due to the head movement can characterize a sound direction only if the exact kinematic properties of the particular head movement are taken into account. Two sets of sensory data enter into the perceptual process of localization, (1) the changing binaural cues and (2) the data representing the changing position of the head. It is the latter with which this paper is concerned. The manner in which they are secured is the object of this investigation.

I. The Role of Head Movement in Auditory Localization

It has been shown that the binaural cues for sound localization, time difference and difference of intensity, convey the angular distance of the given sound direction from the axis of the ears. Thus, they only determine how far from the median plane, on the left or on the right side, the given source of sound is located. Whether it lies in front or in the rear, above or below the horizontal plane, remains undetermined, and the same is true of the amount of its elevation. The angular distance of the given sound direction from the aural axis which is actually determined by the binaural cues has been called the lateral angle (ψ), and it is treated in this paper as if it were a directly given sensory datum.[3] This lateral angle can be counted from either pole of the aural axis.

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[3] This is the terminology employed in paper II. In paper I, the term lateral angle refers to the complement of the angle ψ and is called φ. φ is thus the angular distance of the sound direction from the median plane and was chosen to represent the lateral angle for historical reasons. The motive for changing to ψ was the greater ease with which the angle ψ can be visualized.

If it is 90°, the sound direction lies in the median plane of the head. It follows that *the binaural cues determine merely a range of directions, any of which would, if actually presented, produce the same binaural stimulation.* It is significant that such a range of possible directions for a given sound is never perceived. We hear a sound that appears for the most part in one definite direction. It has been shown that this is due to head movements during the perception of the sound. A motion of the head will, in most cases, alter the position of the aural axis and at the same time change the angle between the latter and the given sound direction. It will be seen shortly that this change of the lateral angle can define the direction of the source of sound; and actually the perception of the proper direction is achieved through a head movement affording such a change of the lateral angle.

In order to show that the change of the lateral angle with the head movement can define a direction, we shall consider a number of particular cases. We shall at first assume that the head is turned about a vertical axis, so that the displacement of the aural axis occurs in the horizontal plane. If the given direction lies in the same plane, the angle between this direction and the aural axis (the lateral angle) changes by the amount of the displacement of the aural axis. This is obviously no longer true when the given direction is not in the horizontal plane, but is above or below. While in the case of the horizontal direction the lateral angle is measured within the horizontal plane, in the case of an elevated direction the angle between this direction and the aural axis extends in an oblique plane. It can easily be seen that this angle is affected to a lesser degree by a shift of the aural axis in the horizontal plane than is the lateral angle in the case of a horizontal direction. If the reader finds himself unable to visualize these spatial relations, the following consideration will lead to the same conclusion.

Take the case in which the direction is exactly vertical. The direction then exactly coincides with the axis of the head movements, and the displacement of the aural axis will not alter the lateral angle at all. It remains 90° throughout the head movement. This is the extreme case. For all other directions the lateral angle will be changed by a displacement of the aural axis. A direction may be given 60° above the horizontal plane, and, before the head movement starts, exactly in front. At this stage, the lateral angle amounts to 90°. When a movement of the head by 90° brings the direction in the lateral position, the lateral angle will amount to 60°, the aural axis still lying in the horizontal plane with the direction 60° above it. A 90° shift of the aural axis thus brings about a 30° change of the lateral angle. For a horizontal direction, on the other hand, a like displacement brings about a 90° change of the lateral angle, as we have seen, while for the vertical direction the lateral angle does not change at all. These three cases are sufficient to suggest what can be learned directly from a visualization of the spatial relations, namely, that the amount by which the lateral angle changes varies with the elevation of the direction. For a given head movement this change is maximal when the direction lies within the horizontal plane, and decreases as the direction approaches the vertical.

Thus the angular distance of the direction from the horizontal plane (angle of elevation) varies with the rate of change of the lateral angle and is determined by it. For a given lateral angle, there are however in most cases four directions, which have the same angular distance from the horizontal plane: in front and in back, above and below. Of these, the two in front are distinguished from the two in back by another feature of the change of lateral angle, the direction, viz., the sign, of the change. When the head is turned to the left a direction in front will shift toward the right side of the head. For the same head movement, a direction in back will shift toward the left side of the head. That is to say, for a direction in front the lateral angle decreases toward the right, for a direction in back it decreases toward the left, and the two directions may thus be distinguished, although both may have the same elevation, and consequently the lateral angle will change for both at the same rate. Only one ambiguity remains: two directions in symmetrical position with respect to the horizontal plane, one above and the other below, are so far not distinguished.

These considerations concerning the rate and the direction of the change of lateral angle are independent of the particular spatial orientation of the head movement. The angle of elevation does not, of course, refer to the horizontal plane as such, but to the plane in which the aural axis is displaced by the head movement, which in the particular case we chose coincided with the horizontal plane. Our considerations apply as well to such a case as a movement about a horizontal axis, that is, a tilting of the head from side to side. Here the aural axis shifts in a vertical plane, the 'angle of elevation' extends toward the front or the rear, and above and below now play the same rôle as front and back did in the case in which the head was turned. They are distinguished from one another through the direction of the change which the lateral angle undergoes due to the tilting motion.

When, upon a movement of the head about a vertical axis, two directions remain which are both consistent with the given change of lateral angle, one above and the other below the horizontal plane, a subsequent tilting of the head, or any motion which contains the tilting as a component, can distinguish between the two possibilities. In fact, natural head movements are rarely accurate revolutions about a constant axis; they must rather be described as revolutions with varying axis. This does not interfere with the qualification of the head movement for procuring a change of lateral angle which can determine a sound direction to the extent indicated above. But the displacement of the axis which occurs during the head movement probably suffices to remove the ambiguity which would result from an accurate revolution about a constant axis.[4]

We have found a number of different movements of the head to be effective in sound localization. The most frequent natural head movement is a turning of the head upon which a tilting to the side is gradually superimposed as the motion approaches the end of the excursion. In the syn-

[4] For a more detailed discussion of this point *cf.* 1 §7.

thetic production of sound directions which were previously reported, a revolution about a vertical axis, in which all components of tilting to the side had to be strictly excluded, was successfully used. In another group of these experiments the head movement was even more artificial; it consisted of a tilting of the head from side to side. With such unnatural movements most accurate localizations were achieved. We are probably justified in saying that any movement of the head which involves an angular displacement of the aural axis can be effective in sound localization. That a head movement which does not involve such a displacement of the aural axis must be ineffective is evident. No change of lateral angle can result from it. Such a head movement is a revolution about a horizontal axis extending from the left to the right, as it occurs in a straight nodding. It is, of course, also ineffective as a component in a kinematically more complicated natural head movement. Briefly, any head movement may be effective to the extent to which it contains as a component a revolution about an axis which lies in the median plane of the head.

The tests which will be reported in the next section are performed with synthetically produced sound directions. The manner in which sound directions can be synthetically produced has been thoroughly discussed in a previous paper; thus only a general outline will be presented in the following.

In experiments on synthetic production, the binaural stimulation which a given objective sound direction would have produced is brought about without actual presentation of this sound direction. We have seen that for a given position of the head the binaural stimulation which is produced by a given sound corresponds to quite a number of directions. All directions which have the same lateral angle produce the same binaural stimulation. Thus, so far as binaural cues are concerned, any one of these directions can be substituted for any other one. Where the lateral angle of a given direction changes in a characteristic way during a head movement, this direction can be replaced by a series of other directions which together present the same changing lateral angle. For every position through which the aural axis passes the lateral angle can be ascertained, and an equivalent direction can be substituted for the given direction. In practice one need not even consider an infinite number of such positions because a differential threshold exists in discrimination of the lateral position of a sound. Of two positions of the head for which the lateral angle is merely subliminally different, only one need be taken into account. We find it sufficient to consider separate positions which are as much as 3° apart. For the synthetical production of a certain sound direction, a definite head movement must be selected. Separate positions through which the aural axis passes during this head movement are chosen 3° apart from each other, and for each of these positions the lateral angle of the direction which is to be produced is ascertained. Thereupon, for each of these positions a direction can be selected among those which have the specific lateral angle ascertained for this position. In this way a series of directions is obtained which are equivalent to the direction which is to be produced, if each is presented at the moment when the head in its movement passes through the position to which it belongs. For the presentation of each of these different directions at the proper moment, the head of the observer is attached to a switch with 20 contact points. Each of these contact points is connected with a loudspeaker. In a particular experiment the switch permits only that movement of the head which is chosen in planning the experiment. It is always a revolution about a constant axis lying in the median plane of the head. During such a movement a contact spring slides over the contact points one after another, thus connecting each loudspeaker in turn. With every 3° displacement of the aural axis the center of another contact point is passed. The position of head and aural axis at the moment when the center of each contact point is passed can easily be ascertained, and the corresponding loudspeaker is placed in the direction which has previously been chosen to present the proper lateral angle for this particular phase of the head movement. When all the loudspeakers are arranged in this manner, the apparatus achieves precisely what is necessary for the synthetic production of the sound direction. While the head is moved, directions are presented which are equivalent to the direction to be produced. Together they present the same sequence of lateral angles which the synthetic sound direction would bring forth if it were actually given. In such experiments the physically given sound directions differ widely from the synthetic directions which are perceived.

In previously reported experiments the twenty loudspeakers which presented the sound were arranged in front of the observer, while the synthetic direction was, for instance, in back of or above the observer's head. In another experimental arrangement the observer perceived a sound directly in front, while all the actually presented directions lay above his head, distributed from left to right. Localization functioning on a basis other than the head movement principle should lead to the perception of sound in the directions actually presented or in their general neighborhood. If nevertheless the synthetic direction is perceived, one can be sure that it is solely on the basis of the head movement principle.

II. Passive Displacement of the Aural Axis

So far we have consistently used the term head movement. Yet, according to the discussion in Section I any change of position of the head which involves an angular displacement of the aural axis, no matter how it is brought about, must suffice to procure a characteristic change of lateral angle. In the abstract, it should not matter whether an observer turns his head actively, or turns on his heel, or swings passively on a revolving chair, if the same displacement of the aural axis results. We have already pointed out, however, that two sets of sensory data enter into the perceptual process of sound localization, the changing binaural cues which represent the change of the lateral angle and the data which characterize the displacement of the aural axis. Without the latter, the change of lateral angle has no significance for sound localization. The nature of the stimulation which represents the displacement of the head will vary with the manner in which the displacement is achieved, and therefore this manner may be very significant. In fact, any stimulation which is capable of coöperating with the binaural cues in sound localization should be investigated. For this reason the various ways in which the head can be displaced will now be examined.

Three kinds of sensory data may represent a displacement of the head: proprioceptive stimulation from the muscles engaged in active motion, stimulation of the eyes, and stimulation of the vestibular apparatus. Usually all three are present, but in experimentation one or another may be excluded, and thus the significance of each kind may be examined. However, one of them, the vestibular stimulation, cannot be eliminated where spatial displacement of the head is involved; it will be always present. It should therefore be investigated first.

In order to eliminate the optical cues for his motion and the proprioceptive stimulation which would result from active bodily movements, the observer was blindfolded and placed on a revolving chair on which he could be turned about a vertical axis. A back rest and a foot rest as well as a rest for the chin served to decrease the slight stresses which arise when the acceleration is conveyed through the body from the parts in contact with the chair. Except perhaps for stimulation resulting from these stresses, the observer was made aware of the chair's and his own movements only through the function of the vestibular apparatus. The sounds which were to be localized under these circumstances were presented in exactly the same way as in the experiments on synthetic production. This was necessary because of the existence of a secondary factor in sound localization, the effect of the pinnæ,[6] which has no connection with the head movement principle, and which might possibly have affected the results. By presenting a synthetic sound direction, a differentiation between the effect of the head movement and the effect of this secondary factor becomes possible.

In the experiments we shall report here the displacement of the head was a revolution about a vertical axis. The loud-

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[6] *Cf.* I §18 and II p. 273.

speakers were arranged in a single row in the horizontal plane, *i.e.*, the same plane in which the aural axis was displaced. The first test made with passive displacement and with blindfold was the synthetic production of a horizontal direction in back, with the row of loudspeakers in front. For this experiment the loudspeakers had to be arranged at distances of 6° from each other, the angles measured from a point which in the actual experiment coincided with the center of the observer's head.

It can easily be shown that this arrangement is suitable for the synthetic production of the desired direction: For a certain position of the head, the direction to be produced may lie straight in back. To this position of the head a position of the switch may correspond in which the contact spring touches exactly the center of a contact point. The loudspeaker which is connected with this contact point is placed straight in front of the observer. Thus its direction is equivalent to the desired direction, for in the case of both directions the lateral angle is 90°. Now we assume that the observer turns his head 3° to the right. This displacement turns the switch by one contact, and at the same time brings the desired direction in back closer to the right pole of the aural axis. The lateral angle of the desired direction decreases by 3° and is 87° for the resulting position of the head. The loudspeaker which is connected with this new contact point must be placed in a direction which has a lateral angle also of 87°. When this is done, its position is 6° to the right of the previously placed loudspeaker, that is, 3° closer to the right pole of the aural axis on account of the change of lateral angle, plus another 3° because the aural axis itself is displaced to the right by 3° with respect to the position for which the first loudspeaker was placed. The center of the following contact point is reached after another 3° of displacement of the aural axis; the lateral angle of the desired direction in back decreases again by 3°, and again the corresponding loudspeaker must be fixed in a position 6° to the right of the one placed just before, that is, 3° to account for the changed position of the aural axis and another 3° to account for the decrease in the lateral angle. The same procedure is, of course, applicable to the placing of all the following loudspeakers in the row and can also be applied to those which lie to the left of the loudspeaker placed first. Each is 6° distant from the next.

In an actual experiment when the observer's head is turned to the right by a certain angle, the sound will shift to the right by twice that angle, appearing in one loudspeaker after another, and when the head is turned to the left, the sound will be displaced to the left in the same manner. Thus, as the head is turned back and forth the sound slides through the row of loudspeakers at twice the rate of the rotation of the head. To stress again the essential point: this sliding sound will present to the observer the same sequence of lateral angles which characterizes the desired direction in back, no matter how quick or how wide the excursion of the head may be, provided that it occurs within the range of the switch. With 20 contact points 3° apart, the switch allows a maximum displacement of the head of 60°, and stops on the switch confine the head movement to this range. The 20 loudspeakers 6° apart cover an angle of 120°, and this is the corresponding maximum displacement of the sound.

Before the observer was seated, the position of the revolving chair was carefully adjusted so that its axis of revolution was in line with the axle of the switch which was, of course, in these experiments, also in a vertical position. After the observer had been placed on the chair, he adjusted his posture until his head could be fastened to the switch; for the switch had to remain in its position relative to the chair, and only its height above the floor could be altered. When the head was fastened, the chin rest was moved up and was fixed in the proper position. Then the observer was blindfolded. In all experiments reported in this paper, orchestra or piano music from victrola records was presented. When the music was turned on, it issued from one of the loudspeakers. From which one it came depended upon the accidental position of head and switch at the moment. The experimenter began to turn chair and observer back and forth, and the physical sound underwent the corresponding shifts. After a few excursions, interrupted by short pauses, the music was interrupted, and the observer was asked from where he had heard it.

All five observers who took part in this experiment heard the sound in the desired direction in back. When the experiment was varied in such a way as to bring the loudspeakers in back of the observer, the result was again positive for all observers: the sound appeared in front. As a further check, the switch was so constructed that the mechanical connection between the attachment of the head, on the one hand, and the switch proper, on the other hand, could be interrupted. In this case the contact spring remained at rest and one particular loudspeaker was constantly connected, while the observer was turned back and forth as before. When this was done during the presentation, the place of the perceived sound changed immediately; now it appeared in the direction of the sounding loudspeaker.

In the synthetic production, the sound was not only perceived on the reverse side in all cases, but in 9 of the 10 trials its direction was also exactly horizontal. Only in one case did the sound appear 25° above the horizontal plane. It will be shown below that under the conditions in question this direction could not possibly have been distinguished from a horizontal direction, and that it likewise represents a satisfactory result.

The positive results of these tests show clearly that sound localization based on the head movement principle is possible, even if the observer is passively turned and blindfolded. Yet they do not enable us to make an estimate of the accuracy with which the localization is achieved under these conditions. Firstly, localization within the horizontal plane, the only one we have as yet demonstrated, seems to be generally favored. If, for some reason, the data given for the localization of an elevated direction are inadequate, the sound is usually heard in a horizontal direction. Secondly, under our experimental conditions, the displacement of the aural axis occurs strictly in the horizontal plane. It has previously been pointed out that sound directions near the plane in which the aural axis is displaced (the equatorial plane of the head movement) are poorly defined. The reason for this fact is purely geometrical. In order to ascertain numerically how much the lateral angle of an elevated direction changes with a given head movement, one makes use of the following formula

$$\sin(90^\circ - \psi) = \sin\beta \cdot \cos\vartheta,$$[6]

where ψ stands for the lateral angle (the angle between the sound direction and the aural axis), ϑ for the angle of elevation of the given direction above the plane in which the aural axis is displaced, and β for the angle by which the aural axis is displaced within this plane. According to this expression, the rate at which ψ changes with changing β is largely dependent upon the cosine function of the angle ϑ. Now the cosine function shows little change for the angles between 0° and, say, 30°. Applied to the present case this means that for directions of smaller elevation the rate of change of the lateral angle is practically the same over a considerable range of directions, and a direction which is determined by such a rate of change will be poorly defined in spatial terms. This, incidentally, furnished the explanation for our accepting a 25° elevated direction as a satisfactory result in the experiment under discussion. The rate of change for this direction is not different enough from the one which characterizes a horizontal direction to afford a discrimination. It may be added that under ordinary circumstances these conditions do not constitute a real difficulty for sound localization. As noted above, natural head movements are revolutions with varying axis, and with an approach of the axis toward the given direction conditions for a sharp determination of this direction improve rapidly.

In order to determine how accurately a blindfolded and passively moved observer can localize, and especially how his achievements compare with results under normal conditions, a direction was synthetically produced which had an elevation of 60° above the horizontal plane—in back when the loudspeakers were in front, or vice versa.

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[6] *Cf.* 1 p. 245, where $\varphi = 90^\circ - \psi$.

The arrangement of the loudspeakers followed the same general procedure as that employed in the first experiment. As the desired 60° direction, one in back of the observer's seat was chosen. That contact point on the switch was ascertained which was connected when this direction fell into the median plane of the observer's head; and the corresponding loudspeaker was placed straight in front of the observer. A displacement of the aural axis by 3° would change the position of the switch so that the next contact would be closed. At the same time the aural axis would come somewhat nearer the desired direction, and the lateral angle would decrease. Yet this decrease would not amount to a full 3° as in the first experiment. An elevated direction, we have seen, corresponds to a change of lateral angle which is smaller than the displacement of the aural axis by which it is caused. Just how great this change will be can be computed from the formula given above. We let β equal 3° and substitute for ϑ the value 60°, that is the elevation of the desired direction above the horizontal plane, the plane in which the aural axis is displaced. Thus we obtain for ψ the value 88° 30′. Once we know the value of the lateral angle, the loudspeaker corresponding to the contact point in question can easily be placed. The loudspeaker which was placed first had a median position; its lateral angle was 90°. If the displacement of the aural axis is clockwise, the new loudspeaker must be placed to the right of the first one, that is, closer to the right pole of the aural axis; for a clockwise displacement brings the desired direction in back nearer to this pole. In order to determine its exact place we have to take into acccount the fact that, because of the displacement, the first loudspeaker is no longer in a median position. It now lies 3° to the left of the median plane, that is 93° from the right pole of the aural axis. Thus the new loudspeaker must be placed 4° 30′ to the right of the one placed first in order to make its lateral angle 88° 30′. In other words, of the 4° 30′ angular distance between the two loudspeakers, 3° account for the different positions of the aural axis when one or the other speaker is connected, and 1° 30′ account for the change of lateral angle which takes place when the head passes from one position to the other.

The position of the next loudspeaker may be found in the same way. β has here the value 6°, while ϑ, of course, remains 60°, and the result obtained for ψ is 87°. For the corresponding position of the head the first loudspeaker lies 6° to the left of the median plane, while the new one must be placed $90° - \psi = 3°$ to the right of the median plane, *i.e.*, $\beta + 90° - \psi = 9°$ to the right of the loudspeaker placed first. This loudspeaker is the starting point with reference to which the other loudspeakers are placed. In this manner all the loudspeakers on the right of the first are arranged. Those on the left side are to be arranged in the same way, with the qualification that here all angles refer to the left pole of the aural axis. When the head of the observer is fastened to the switch he must face the first loudspeaker directly, while the position of the switch must be such that this loudspeaker is connected.

In the actual test the procedure was exactly the same as in the first experiment. The experimenter turned chair and observer swiftly back and forth so that the velocity of the displacement approximated the speed of active head movements. Here again the observer could face the loudspeakers and have the desired direction in back, or vice versa. It seems that the situation in which the desired direction is to appear in front is more favorable, because directions in front are psychologically better defined than directions in back. Thus, most of the tests were done in this manner.

With elevated directions there is always the problem of how the observer is to indicate the direction of the sound. He can give an estimate of the elevation in degrees or he can point in the direction of the sound. Neither method is very accurate, and constant errors probably occur in both. The observer was allowed to choose between the two methods and encouraged in the use of both at the same time. Where both data are available they are indicated in the table. With one exception the 15 observers had only one trial.

TABLE

Subject		Blindfolded	Not Blindfolded
I	*b*	60° *p*, 60° *est*	same
II	*b*	60° *est*	60° *est*
III	*b*	55° *p*, 50° *est*	same
IV	*b*	60°–80° *est*	52° *p*
V	*f*	65° *p*, 80° *est*	same
V	*b*	55° *p*	same
VI	*b*	50° *p*, 60° *est*	60° *p*, 60° *est*
VII	*f*	45°–50° *est*	same
VIII	*b*	45° *p*	65° *p*
IX	*f*	40° *p*, 40° *est*	60° *p*
X	*b*	35° *p*	41° *p*
XI	*b*	30° *est*	70° *est*
XII	*f*	30° *est*	50°–60° *est*
XIII	*b*	20° *p*	70° *p*
XIV	*b*	10°–20° *est*	53° *p*
XV	*b*	10° *p*	64° *p*

Desired direction = 60°.
b = loudspeakers in back.
f = loudspeakers in front.
p = subject points in the direction of sound image.
est = subject estimates its elevation.

The results are given in the first column of the table. The observers are listed in the order of their success in this experiment. The results of the first 6 are satisfactory, and the remaining judgments are too low.

With each observer a variation of this experiment was performed. The blindfold was removed from the observer's eyes, the experimenter gave the impression of changing the apparatus so as to suggest quite a different experiment, and then proceeded just as he had done before. The results are listed in the second column of the table. Without the blindfold, 13 of the 15 observers showed quite satisfactory results. This means that 7 observers showed a definite improvement over their performance when blindfolded. The two who did not give satisfactory results (VII and X) were tested again with the chin rest removed so that active head movements became possible. The results showed no change of the direction they perceived. Apparently these subjects belonged to that large group who generally underestimate the elevation of any steep direction. The constancy in the results of these observers makes this interpretation plausible.

Two facts emerge from these results: Firstly, a sizable number of observers is able to localize sound adequately with passive displacement of the head and with exclusion of sight, that is, largely on the basis of vestibular stimulation. Secondly, all observers when passively moved are able to localize if vision is *not* excluded at least as well as they would do with active head movements. Under the given experimental conditions the first fact is quite remarkable. A revolution of the head strictly about a vertical axis does not entail a change of the direction of the gravitational force relative to the vestibular apparatus; only forces of acceleration give rise to stimulation of the vestibular system. This means that no direct cues for the position of the head at a given moment are obtained in the vestibular system. Even the velocity of the displacement of the head can only indirectly be derived from the stimulation; for only acceleration and not velocity as such can stimulate the vestibular apparatus. In whatever manner the displacement of the head is functionally represented in the process of sound localization, whether as a sequence of positions or as a rate of change,[7] the original sensory data have to undergo a transformation. These circumstances together with the fact that here the vestibular data are to be evaluated quantitatively raise a new problem in the field of vestibular function. The following considerations may help to form an estimate of the accuracy with which the vestibular data must represent the actual head movement in order to make possible the localizations which were obtained in this experiment.

As can be seen from the figures given above, in this experiment the loudspeakers close to the original one are 4½° apart. Roughly this is also true of the others. Since the contact points on the switch are 3° apart, the shift of the sound direction actually presented is 1½ times as great as the corresponding displacement of the head. In the experiment first reported the shift of the sound is twice as great as the displacement of the head, and the image of the sound appears hori-

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[7] With respect to the achievement of sound localization these two possibilities are equivalent.

zontally opposite the loudspeakers. Another case which we may consider here is the one in which the image of the sound is directly overhead. As will be seen below, in this case the shift of the sound actually presented is as great as the displacement of the head. In short, if the ratio of the displacement of the sound to that of the head is 1, the sound image is straight above; if the ratio is 1½, the image is elevated by 60°; and if the ratio is 2, it is horizontal. A simple calculation shows that in the present case, where the ratio is 1½, an overrating of the actual displacement of the head by 50 percent due to insufficient sensory data would make this ratio 1, and accordingly the sound image would appear straight above; whereas an underrating of the actual displacement by 25 percent would make the ratio 2, and the sound would appear horizontal. Thus, in this case an underrating of a displacement of the head affects the perceived direction more strongly than an overrating of the same order.

An examination of the table shows that practically all the inadequate localizations which occurred were too low. This may be explained by the asymmetry with which inaccurate sensory data for the displacement of the head affect the perceived direction. In spatial terms, an inadequately determined direction may thus have a better chance of being heard below the desired direction than above. However, the simple assumption that with vision excluded the displacement of the head is underrated rather than overrated could also account for this finding, and in the experiment to be reported next, this latter explanation seems to be the proper one.

A sound image vertically above the observer was synthetically produced. In this case the arrangement of the loudspeakers is especially simple. A sound direction vertically above is characterized by the fact that the sound remains within the median plane when the head turns about a vertical axis; the lateral angle remains 90°. Thus, during such a displacement, the lateral angle does not change at all, and the rate of change is, of course, also zero. In order to duplicate these conditions in a synthetic experiment, the sound actually presented in the horizontal has to shift in such a way as to maintain a constant lateral angle of 90°. This is the case, when the actually presented sound is always either straight in front or straight in back of the observer's head. One achieves this by giving the loudspeakers angular distances of 3° from each other, the same as the angular distances of the contact points on the switch. While the observer's head is being attached, the switch is in a position which connects the loudspeaker straight in front or back. Under these conditions the actually presented sound is located in the median plane for any position of the head. When the head is thus attached, the experiment can proceed in the same way as the one reported above.

Of the 10 subjects who took part in the experiment, two were unable to localize the sound in the region overhead, even under favorable conditions. One of them always heard it in the rear about 60° high, and the other one horizontally in front or in back. The results for the other 8 subjects are as follows: 90°, 90°, 90°, 80°, 75°, 75–70°, 70°, 70°; here 90° represents the vertical, the other angles refer to directions slightly in back of the vertical. Thus, when blindfolded, 3 of the observers heard the sound in the desired direction, and the others localized it from 10 to 20° too far back. When the blindfold was removed, they all had the image of the sound vertically above. Again all deviations from the desired direction corresponded to an underrating of the displacement of the head; and since here misrepresentation of the actual displacement of the head in either sense leads to the same amount of deviation in spatial terms, we can safely adopt underrating of the displacement as the explanation. A simple calculation shows that an underrating of the displacement by 25 percent accounts for a deviation of 20° toward the back, which is the maximum which occurred in this experiment. In another respect this experiment confirms the result of the preceding one: There are subjects who can adequately localize merely on the basis of vestibular cues derived from acceleration, and with the others inaccuracies are restricted to what corresponds to a misrepresentation of the displacement by 25 percent. With the aid of vision, moreover, passive displacement is just as effective as active head movements.

The distinctly directed deviations from the desired direction which were found in these experiments seem to me of particular interest for the theory of sound localization. They obviously cannot be regarded as the result merely of an indistinct perception. In a purely geometrical sense there are two ways in which the elevation of a direction can be characterized by the behavior of the lateral angle during a displacement of the aural axis. One way is that the amount of change of the lateral angle referred to the displacement of the head as such characterizes the perceived direction, as has just been discussed. The value of this quotient would here directly determine the process which corresponds to the perceived direction.

The other way was brought out in the discussion of the maximal differences in the change of lateral angle which may occur with different elevations of a source of sound: the range within which the lateral angle of an elevated direction can change depends upon the elevation above the plane in which the aural axis is displaced. The greater the elevation of the sound direction above this plane, the smaller the range of variation of the lateral angle. For a head movement about a vertical axis, for instance, the lateral angle for a direction elevated 60° above the horizontal plane varies only within a range of 30°. An extreme case is the vertical direction; its lateral angle does not vary at all. No matter how far the head is displaced, the smallest value which the lateral angle of an elevated direction can assume is obviously the same as its angle of elevation above the plane in which the aural axis shifts. Thus the limiting value of the lateral angle can directly define the elevation of a direction. This constitutes the other way in which the elevation of a direction might be characterized by the behavior of the lateral angle.

It is clear from the outset that the second principle cannot alone be responsible for sound localization. Long before head movements produce the limiting value of the lateral angle, accurate sound localization may be achieved. The question is rather whether the second principle—which *geometrically* is strictly connected with the first—plays a secondary rôle in sound localization. In other words, are geometrical relations so fully represented in the process of sound localization that, because the first principle holds, the second—its geometrical corollary—must also hold?

In this connection, the most interesting case is that of the vertical direction because here the second principle could yield as strict a determination as the first. If we say that a sound is heard above because its lateral angle does not change at all but remains 90° throughout, this statement as such could be interpreted in terms of both principles. In terms of the first we might say that the lateral angle does not change, and in terms of the second that it remains *90°*. Either one of the arguments would suffice to characterize the direction. But the question is whether both principles are actually involved in the process. Here the experiment which we have just reported is decisive. When visual cues for the displacement of the head are excluded, the perceived direction is often definitely too low. Since these deviations always disappear when the blindfold is removed, they seem to be due to the insufficiency of available *data for the displacement of the head, more specifically to the fact that the displacement* of the head is underrated. The sound is heard at an elevation of 70° or 80°; and yet the actually presented sound is given in the median plane, *i.e.*, with a lateral angle of 90°. If the second, the limiting, principle were effective, this could not occur.

We must therefore conclude that this second principle plays no rôle in the process of sound localization. It is merely the *amount* of the change of the lateral angle referred to the displacement of the head which is effective in determining the elevation.

III. The Selective Principle

Before further experiments are reported in which sound localization is based on *visual* cues, it seems advisable to discuss briefly a general selective principle which is implied in all sound localization. This principle becomes particularly obvious in experiments in which sound directions are synthetically produced. Why is it, one may ask, that the desired direction is heard instead of the actually presented sequence of directions? Obviously because this direction is at rest whereas the actually presented sound shifts in space while the head is being displaced. Apart from this selective principle, the actually presented sequence of directions and the direction which is perceived are, according to our previous discussion, entirely equivalent. They produce, with the head movement in question, exactly the same temporal pattern of binaural stimulation. We know that almost every lateral angle can be represented by a number of different directions, and that a given sequence of lateral angles can thus be represented by a nearly endless variety of patterns of subsequent directions. But in a given case this sequence of lateral angles, no matter how it is produced, gives rise to one percept only, that of a *stationary* direction which is compatible with the sequence.

For the sake of simplicity we shall confine this discussion to sequences in which each succeeding direction is contiguous with its predecessor, *i.e.*, cases where the presented sound shifts steadily and, moreover, in a plane. Even in this simplest case it may be hard to visualize the spatial relations which result from the circumstance that both the presented sound and the head are displaced. The task becomes easier if one chooses the head as frame of reference. With reference to the head, all directions which realize a given sequence of lateral angles are displaced during the head movement, the actually perceived one as well as the others. Objectively, the percieved direction is distinguished from the others only by one fact. The perceived direction is covariant with further objects which are given in our environment by other senses and which are, of course, also displaced with reference to the head when the head is being turned. We thus arrive at the following formulation of the principle of rest which I believe to be the most adequate: Of all the directions which realize the given sequence of lateral angles, that one is perceived which is covariant with the general content of surrounding space.

It is significant that the principle of rest must apparently be regarded as the limiting case of a more extensive principle which, although not overt in ordinary sound localization, seems to indicate the general way in which the selection is made. This broader principle was demonstrated in synthetic production of sound directions when sequences of lateral angles were presented for which no stationary direction existed. It was named the principle of least displacement. If a sequence of lateral angles is presented to which no stationary direction corresponds, the sound is perceived in the region where it has to undergo the smallest displacement in space while realizing the given sequence of lateral angles.

Suppose a sound direction vertically above is to be synthetically produced by means of a sound that shifts in the horizontal plane. In this case the arrangement of the head switch and the loudspeakers must be such as to leave the actually presented sound in the median plane of the head. This is the condition which must be fulfilled if the desired vertical direction is to be obtained. Consequently the angular distances of the contact points and of the loudspeakers will have to be the same, and if the head is fixed to the switch in such a way as to connect at the start the loudspeaker straight in front, the sound travels about during the head movement so that it is at any moment straight in front of the head. If, on the other hand, the head and the switch are connected, when the loudspeaker in question lies, for instance, 25° to the right, the sound will, during the head movement, always remain 25° to the right of the median plane of the head, *i.e.*, at a lateral angle of 65°. No stationary direction corresponds to this sequence. The only case in which a sound at rest can be produced with a constant lateral angle is that in which this angle amounts to 90°. Here, it will be remembered, the sound image appears in the direction of the axis of the revolution of the head. When the lateral angle remains constant at 65° the sound is perceived at an elevation of about 65° to the right of the median plane, that is as close as possible to the axis of the displacement. Here it moves about in correspondence with the displacement of the head.

It is obvious that at any lower elevation the shift in space necessary for the realization of the given sequence of lateral angles would be greater. The closer the sound to the axis of the revolution, the smaller is the displacement of the sound image in space. In accordance with the principle of least displacement, the sound is actually perceived in maximal proximity to that axis.[8]

IV. Rotation of the Visual Field

In Section II of this paper, experiments were reported in which both proprioceptive stimulation resulting from active head movements and visual cues for the displacement of the head were excluded. Quite substantial achievements in sound localization were shown to occur when only vestibular stimulation was thus admitted. If visual cues for the displacement of the head were added to the vestibular stimulation, they improved the achievements and even made them optimal The question will now be examined of whether visual data *alone* can represent the displacement of the head in sound localization.

In order to eliminate vestibular stimulation, it seems to be necessary to keep the observer physically at rest and bring about a psychological state of motion by means of induced ego-movement. When an observer is placed inside a revolving screen he will, after a while, no longer perceive the surrounding screen in motion; rather he will feel himself rotating in a direction opposite to the objective movement of the

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[8] Another experiment in which the principle of least displacement determines the result is reported in 1 §22.

screen. The question is, of course, whether with respect to sound localization the optically produced state of phenomenal movement is functionally equivalent to real movement; in other words, whether optical stimulation can replace vestibular stimulation.

The revolving screen used in this experiment was made of white cloth which hung down from the edge of a large wheel fixed in a horizontal position underneath the ceiling. It thus formed a hollow cylinder 43″ in diameter. On the inside it showed vertical black stripes on a white ground, 2¼ inches wide and 6¾ inches apart. Wheel and screen were turned by a motor at various speeds.[9] When an observer was placed in this small compartment he soon felt himself turning in the opposite direction, and soon afterwards the screen appeared to be at rest. When now the observer looked down at the floor, he saw it turning in his own direction and at the same rate. The spontaneous transition from rest to motion was often quite disagreeable, but once the screen had come to phenomenal rest, as a rule no giddiness was felt. When the state of complete ego-movement was attained, there was never a spontaneous change back to the first state in which the observer is at rest and the screen moves. The transition to ego-movement was facilitated when some object was placed inside the screen upon which the observer could let his eyes rest. The observer was instructed to look steadily at a vertical rod which was placed before him and as close as possible to the screen. Soon after the screen began to turn the rod showed induced movement in the direction opposite to the movement of the screen; and gradually the observer felt himself joining in this motion until after a while, with the cessation of the phenomenal movement of the screen, the state of induced ego-movement became complete. Thus the momentary giddiness which often accompanies the transition to ego-movement could be eliminated.

A sound which remains in the median plane when the head is turned will be perceived in the direction of the axis of the

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[9] One revolution in 7 seconds proved to be a comfortable rate for the screen which was used.

displacement. If this axis is vertical, a sound objectively straight above the head would fulfill this condition. But the same condition is satisfied when a sound which shifts about in the horizontal plane remains throughout in a median position with reference to the head. If induced ego-movement can be substituted for an actual displacement of the head, the same effect can be obtained in an experiment with the revolving screen. A loudspeaker is placed at some distance beyond the screen straight in front of the observer whose head is kept in a constant position by a chin-rest. When now during induced movement a sound is presented in the loudspeaker, the above conditions for hearing a sound vertically above are given: the head of the observer 'turns' about a vertical axis, and at the same time the sound remains always in a median position with reference to the head. In this stiuation the sound is actually heard vertically above. Thus it is shown that induced ego-movement can be substituted for a physical displacement of the head.

The great simplicity of this form of the synthetic experiment lies in the fact that instead of two displacements, that of the head and that of the sound, only the screen is actually moving. In the state of induced ego-movement the revolving screen represents the resting space, and all the objects which are physically at rest are therefore represented in the same state of motion as that in which the observer who is also physically stationary feels himself. The floor of the room and the rod in front of the observer are, as reported above, perceived in this state of motion. The loudspeaker would move about in the same manner, if the observer could see it. Had the distribution of motion and rest which the observer perceives in the state of induced ego-movement been objectively given, this experiment would be an exact duplication of an ordinary synthetic experiment: the head of the observer is displaced about a vertical axis, and the source of sound undergoes a corresponding displacement, so that it always remains in a median position.

Of 15 observers who participated in this experiment, 3 were unable, even under ordinary circumstances, to localize a sound presented objectively overhead. The remaining 12 perceived the sound as vertically above the head, either immediately or shortly after the beginning of the presentation. In the few moments during which it stayed in the horizontal plane it seemed to move about with the observer. When a sound was presented exactly to the side, it likewise travelled phenomenally with the observer, remaining always in the same position with reference to him. Yet, in this case, it remained in the horizontal plane. A sound direction which coincides with the aural axis is strictly determined by the binaural cues alone, just as the pole of the globe is sufficiently defined by its latitude, and needs no longitudinal determination. No other direction produces the same binaural cues, and thus no other direction could replace it.

If the loudspeaker was placed obliquely to the side, say, 30° from the median position, the sound was heard obliquely above where it seemed to move about with the observer. From the above analysis, it is clear that this is an analogue of the experiment on the principle of least displacement which was reported in Section III. All these observations can be made in immediate succession, when the loudspeaker is slowly carried around from a position straight in front of the observer to one on his side. The sound which is at first heard directly overhead descends slowly to a horizontal position.

There is still another experiment which can be performed with induced ego-movement. It corresponds to the first experiment reported in this paper, where a sound actually presented in front was perceived in back, and vice versa. This reversal of front and back was brought about when the actually presented sound direction was displaced by twice the angle of the displacement of the head. When induced ego-movement is substituted for a physical displacement of the head, the same relation of the displacement of the head and of the presented sound can be brought about. During induced ego-movement, it will be remembered, the observer and a stationary sound will be felt in the same state of motion. In order to give the sound *twice* the displacement of the observer it must in addition be physically displaced in the direction in which the observer feels himself turning, and this at a rate which is equivalent to the rate of the observer's subjective motion. If we assume that the subjective rate of motion is (in the opposite direction) the same as the objective rate of the screen, the sound must be objectively displaced with an angular velocity equal to the angular velocity of the screen, but in the opposite direction. Thus, in order to obtain by means of induced ego-movement, the reversal of front and back, we must rotate the screen as well as the source of sound about the observer, the screen in one direction and the sound in the other direction, but both at the same rate.

In order to rotate the sound about the observer, a small dynamic loudspeaker with permanent magnet was fixed to the end of a long arm which could be swung in a circle about the observer. The seat for the observer was fixed on a vertical column consisting of 1½" steel tubing mounted on a heavy iron base. The arm which carried the loudspeaker was rigidly fastened to a wooden block which turned on two ball-bearings about the column between the base and the seat. The block carried a pulley by means of which the arm was turned around. The outer end of the arm was bent up to bring the loudspeaker to the level of the observer's head. Mounted on the base was a reduction gear motor which, through a rubber belt, set pulley, block, arm and loudspeaker in rotation. A heavy lead fly wheel on the main shaft of the motor kept it running at a constant speed. This whole device was placed within the revolving screen with the arm projecting out under the lower edge. The distance from the head of the observer to the loudspeaker was 150 cm. The current for the loudspeaker was carried to the moving parts by two iron wires which, fixed to the block, dipped into circular grooves filled with mercury which were cut into a bakelite block fastened to the base.[10]

The procedure in an experiment was the following. After the observer had been placed on the seat inside the screen, the loudspeaker was made to turn around him. When the proper rate of rotation was reached, the screen was set in motion at a rate previously determined to match the speed of the revolving loudspeaker. The screen turned to the right while the loudspeaker shifted to the left. Soon the observer would find himself in rotation to the left, while the screen appeared to be at rest. Then the sound was presented. Had the observer localized it in the loudspeaker from where it actually came, he would have perceived it moving around in the same direction in which he felt himself moving, only twice as fast. But this never happened. Rather the localization

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[10] The writer is indebted to Prof. E. B. Newman for designing this apparatus.

of the sound was always reversed with respect to front and back. The observer heard it straight in front when the loudspeaker actually passed the median plane in back of him, and vice versa. For some observers the sound was definitely at rest, and they felt themselves passing it as they turned about, just as if they were turning on a revolving chair and were passing again and again a stationary source of sound. Others could not decide whether the sound moved or remained stationary. · Often it was heard moving slowly to the right, that is in the direction opposite to the subjective rotation of the observer and the objective displacement of the loudspeaker. Irrespective of such differences, all 20 observers who took part in this experiment showed the reversal of front and back. When asked "How does the sound behave with respect to you?" all observers reported that it shifted to the right, that is, in the direction opposite to the actual displacement of the sound. This fact is necessarily connected with the reversal of front and back. The binaural cues strictly determine the position of the sound with respect to left and right. Thus the sound is invariably heard on the left when the loudspeaker is on the left and on the right when the loudspeaker is on the right. Suppose now that the loudspeaker travels objectively, for instance, from a position on the left side to a position in back. Since at the same time the phenomenal sound moves from the left to the front, the reversal of the direction of revolution follows.

It may be well to consider how the general selective principle which was discussed in Section III applies to this experiment. Are the directions in which the sound is perceived covariant with the general content of surrounding space? More specifically: Is the sound in its reversed positions covariant with the screen? Let us call the physical position of the loudspeaker when it is straight in back of the observer position 1. In this position the sound is heard straight in front. When in its objective revolution to the left the loudspeaker has shifted by 90° from its position in back to the right side of the observer (position 2), it is actually heard in this position. Meanwhile the screen, too, has been displaced by 90°, and since its rotation is to the right, the part, which was in front when the loudspeaker was in position 1, is now also to the right of the observer. During the next quarter revolution the loudspeaker shifts from the right side to the position straight in front (position 3). At the same time the perceived direction changes from the right side to the position straight in back. Yet the part of the screen which just lay in the direction 90° to the right is now likewise straight in back, because the screen, too, has undergone another displacement of 90°. In the same fashion positions of the screen and of the perceived sound continue to coincide for the remainder of the revolution. Thus we see that the direction of the reversed sound remains always the same with reference to the screen. The selective principle applies to this experiment.

In the state of induced ego-movement the screen appears at rest and consequently the perceived direction should also be perceived at rest. This was actually the case with those observers who reported that they seemed to pass a stationary sound in their apparent rotation. Others, however, heard the sound moving in the direction opposite to their own rotation. This observation cannot be explained in terms of our previous discussion. Purely geometrical considerations lead to the conclusion that the reversed sound direction is covariant with the screen. If the sound is heard in a reversed direction, as is actually the case, this direction must always coincide with a particular part of the screen. However, if in spite of this covariance a moving sound is perceived instead of a stationary one, we have a new problem before us. This problem belongs to the psychology of movement rather than to sound localization.

A last point remains to be mentioned. The reversal of front and back can often be shown to occur when the observer is not yet in the state of induced motion. The stimulus condition alone which eventually results in phenomenal movement of the self apparently suffices to produce the reversal of front and back. Here it should be remembered that, as far as visual stimulation is concerned, the situation in which a subject is actually turning in a stationary screen is entirely equivalent to the situation in the present experiment where the screen turns and the observer remains physically at rest. It seems that a visual stimulation, which is equivalent to that resulting from rotation of the subject, produces the corresponding effect on sound localization, and that this effect occurs regardless of whether the phenomenon of ego-movement accompanies this stimulation.

In Section III two alternative formulations of a general selective principle were offered. The evidence which has just been cited favors one of them. It now seems doubtful that phenomenal rest as such is the factor which distinguishes one direction from all the others which are compatible with the presented sequence of binaural cues. Covariance with the general content of surrounding space, however—whether it is perceived at rest or not—can still be regarded as decisive for the selection of the perceived direction.

SUMMARY

Experiments of synthetic production of sound directions have been reported which show that either vestibular cues or visual cues can replace head movements as such. In one group of experiments the blindfolded subject localized the sound while he was passively turned on a revolving chair, and in the other group the subject observed the direction of sound while seated inside a revolving screen. The results indicate that (*a*) fairly accurate representation of the actual displacement of the head is furnished by vestibular stimulation and that (*b*) visual stimulation, equivalent to that which actual displacement of the head would give, suffices to determine the direction of sound.

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