THE PSYCHOLOGICAL REVIEW.

FROM THE PSYCHOLOGICAL LABORATORY OF
THE UNIVERSITY OF CHICAGO.

THE MONAURAL LOCALIZATION OF SOUND.

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The present paper reports a series of observations upon the capacities of auditory localization in a person entirely deaf in one ear. In several of the experiments we have made parallel observations upon a person of normal hearing, and the cases are presented comparatively, in order to bring out as clearly as possible the peculiarities of monaural localization.

I.

We may conveniently preface the report of our experiments with a brief survey of the current theories of binaural localization.

Two general types of theory have been advanced to account for the ability to localize sounds. One of these, with which the names of Preyer and Münsterberg are associated, refers auditory localization to the action of the semicircular canals.¹ This view has as yet met with no general acceptance. The other type of theory, which is widely maintained by psychologists and physiologists, is formulated with admirable precision in the following words of the British scientist, S. P. Thompson:²

¹Preyer, *Pflüger's Archiv*, Bd. 40, S. 586. Münsterberg, *Beiträge z. Psychologie*, Heft II., S. 182. These writers differ distinctly in their conceptions of the precise *modus operandi* of the canals.

²S. P. Thompson, *Philosophical Magazine*, January-June, 1882, p. 415. This article contains an excellent critical discussion of the theories of Luca, Steinhauser, Graham Bell, Mayer, Mach, Lord Rayleigh and others. Among the best of recent investigations are those of Pierce, *PSYCHOLOGICAL REVIEW*, Vol. I., p. 461, and Matsumoto, *Yale Studies*, Vol. V., p. 1.

"Judgments as to the direction of sounds are based, in general, upon the sensations of different intensity in the two ears; but the perceived difference of intensity upon which a judgment is based, is not usually the difference in intensity of the lowest or fundamental tone of the compound sound (or 'clang'), but * * * the difference in intensity of the individual tone or tones of the clang for which the intensity-difference has the greatest effective result in the quality of the sound."

This statement obviously makes differences in the intensity and quality of the sound sensations perceived by the two ears the fundamental factors in our localizations. Many of the adherents of this general view emphasize the importance of the intensity element, as if that were really the basal fact, and mention difference in quality as though it were somewhat incidental and distinctly of secondary importance. Thompson's formulation puts the matter in an undoubtedly more accurate form. The significant objective difference in sound waves reaching the two ears with unequal intensity is not so much in the amplitude of the fundamental vibration, which gives the sound its pitch, as in the amplitude of the upper partials, which contribute very largely to the timbre or quality of an auditory complex.¹ Generally speaking, then, a difference in the intensity of the sound stimulations reaching the two ears results in the consciousness of a difference in the auditory quality of the two sensations, rather than in a mere perception of inequality in the intensity of the two stimulations. Of course this cannot be the case with pure tones. But it is to be remembered that pure tones are notoriously difficult to localize with any approach to accuracy. Our auditory orientation corresponds, therefore, to the intensive and qualitative difference in the sound sensations of the two ears, and of these the qualitative differences are seemingly much the more conspicuous in consciousness.

¹Thompson (*loc. cit.*) inclines to accept Lord Rayleigh's view that this modification of the partials is due chiefly to the effects upon the sound waves of the bones of the skull, as against Mach's contention that the pinnæ are mainly responsible for the phenomena. Our observations, as will be seen, tend on the whole to confirm Lord Rayleigh's theory on this point. The relative importance of the two factors varies with different objective positions of sounds, and both of them are at times clearly operative.

Unless modified by explanatory corollaries, a formulation phrased in this manner is unquestionably open to the criticism urged by Stumpf¹ and others who follow him. It is somewhat more precise than the earlier statements of v. Kries² and the similar formula of Matsumoto,³ quoted approvingly by Ladd.⁴ But at best it leaves much to be desired on the score of accuracy of expression. When dealing with intensity differences, the explanation which the statement advances requires a perception of the intensity of the sound in one ear as greater or less than the intensity of the sound in the other ear. Or, when expressed in terms of quality, it requires a perception of the quality of the sound in one ear different from the quality of the sound heard by the other ear. Neither statement corresponds exactly to the facts. We are conscious of only one sensation, only one intensity and only one quality. This single sensation, with its intensity-quality attributes, is referred to some objective point in space. We may at times connect it with the predominant or exclusive action of one ear. But in no case is there any real comparison or analysis of the two intensities or qualities proceeding from the two ears.

Undoubtedly on some occasions the physical and physiological conditions resulting in the stimulation of the two ears with unequal intensities give rise to psychical processes involving localization of the sound. And undoubtedly, also, the physical and physiological conditions which are most often encountered are such as accompany differences in the quality of the sounds falling upon the two ears; with which, in turn, localizations may be connected. But this is a very different proposition from the one above quoted, with its implication of a conscious comparison of the intensities and qualities of sounds heard by the two ears.⁵

¹ Stumpf, *Tonpsychologie*, Vol. II., p. 50, ff.

² v. Kries, *Arch. f. Anat. und Physiol.* (Physiol. Abth.), 1877, p. 329. This author has, in a later publication (*Zeitsch. f. Psychol. und Physiol.*, Vol. I., p. 235) criticising Preyer and Münsterberg, made a much broader statement, including more explicit reference to the effects of quality upon auditory localization.

³ *Loc. cit.*

⁴ Ladd, *Outlines of Descriptive Psychology*, p. 191.

⁵ We omit discussion of sounds heard as double, either in binaural or monaural hearing. They do not involve the point we are here discussing. Cf. Stumpf, *loc. cit.*

We learn to localize sounds on the basis of differences among them, which are partly differences of intensity and partly differences of quality, involving sometimes variations in apparent pitch. These differences in intensity and quality have their physical and physiological basis largely in the differences between the stimulations of the two ears. But these physical and physiological differences are not reported in consciousness in the form of sensations connected with the separate ears. The theories which refer auditory localization immediately to these factors are, therefore, primarily engaged with the physical and physiological pre-conditions of the process.¹ Intensity and quality are unquestionably involved in conscious processes of auditory localization, to say nothing of motor and visual elements.² But these formulations with which we have been dealing are in point of fact only secondarily concerned with the strictly psychical phases of the phenomena. We shall take cognizance, in connection with our own work, of both kinds of facts.³

II.

We are now ready to begin the account of our experiments, and we shall anticipate at the outset our most important conclusion, in the belief that we may thus materially clarify our subsequent descriptions and discussions.

In the case of monaural hearing there can obviously be no question of the operation of the intensity factor in the form considered in the previous section. Provided the position of the head is fixed, changes in apparent intensity are, if unaccompanied by changes in quality, wholly ambiguous in monaural

¹ This procedure is much after the manner of the current color theories.

² Münsterberg's account (*loc. cit.*) of the part played in auditory localization by reflex and semi-reflex movements corresponds closely to the accepted view of the more careful psychological writers. This statement in no wise implies assent in such quarters to his theory of the dependence of these movements upon the action of the semicircular canals.

³ It is no part of the present undertaking to go into the merits of the nativistic-empiristic space controversy, and our investigations touch only indirectly, if at all, the problem of the intrinsic voluminousness and extensity of auditory sensations. Our immediate interest is in the fundamental physical and psychical conditions upon which monaural localization depends, and such localization is clearly in a space of the conventional visual-tactual-kinæsthetic kind and not in one of a purely auditory character.

hearing. They may mean change of distance, change of direction, change of actual objective intensity with or without change of either distance or direction, or finally any combination of these factors, and the subject has absolutely no reliable means of determining which of these alternatives is really involved in any specific case.

The qualitative differences already described in the quotation from Thompson are differences connected with variations in the stimulations of two ears. We find that qualitative differences in sounds coming from different directions and falling upon one ear are quite adequate to serve for localizations of considerable accuracy. Monaural hearing involves apparently a system of local signs based on qualitative differences, which are rapidly acquired for any given series of sounds, when not possessed at the time the sounds are first heard. This development is quite independent of any knowledge imparted through channels other than the auditory sensation itself, and independent of any assistance from the turning of the head, which might confirm, by changing the perceived intensity, the original judgment based on quality.

The subject of the experiments is a man of thirty, who lost the use of his left ear, when four years of age, through ulceration of the middle ear consequent upon an attack of scarlet fever. The tympanic membrane was practically destroyed and a scar has replaced it. How far the bones of the middle ear are affected it is not possible to state. The malleus appears, however, to be in place. The internal ear was probably attacked by the disease, of which all traces save deafness disappeared at the age of fifteen. In any case the deafness on the affected side seems to be complete. To assure ourselves of this as far as possible, the subject was examined by an experienced aurist. The Weber test applied with the C fork resulted in strong lateralizing in the intact ear. For both high and low tones complete deafness was demonstrated. The C₄ fork was heard when the intact ear was tightly closed. But it was heard with equal distinctness when the defective ear was also closed, showing that this ear had not participated in the transmission. The test for the duration of bone conduction could not be made,

because of the entire normality of one ear. The evidence points almost conclusively to lesion in the labyrinth.

The subject reports that, since the onset of the disease, he has never had the slightest reason to suppose he hears at all with this ear. The whole region of the external ear is, as compared with the intact side, rather numb in feeling. The normal ear is somewhat unusually acute. The intensive threshold is lower than that of the average person, and the sensibility for tone runs from 16 vibrations per second up to 35,000 per second. The musical capacity is good, with a limen for pitch discrimination rather better than the average. In no respect, however, is the hearing very remarkable.

The subject employed for comparison is entirely normal in every particular and requires, therefore, no further description.

Apparatus.—The apparatus used in these experiments was substantially the same as that used by Pierce and Matsumoto.¹ Our purpose was to give the subject sounds of the same quality and intensity from different directions. Equal intensity was secured by use of the same source of sound—in our experiments a telephone—placed always at the same distance from the head. To secure a uniform distance Pierce and Matsumoto used a spherical cage supported by standards, and so placed that the head of the subject, which was supported by a head-rest clamped to the back of his chair, should be in the center of the sphere. We found it more convenient to suspend our cage (diameter 4 ft.) from the gas-fixture by means of a wire. Using the wire as an axis of rotation, the experimenter could then stand always at the same place and, after attaching the telephone at the proper height, noiselessly turn the cage the required distance. Thus no suggestion of the location of the sound was given by the movements of the experimenter. In order to secure a constant position for the axis of rotation two uprights were fastened to the floor, and the equatorial circle of the sphere rested against them when the telephone-click was given. It should be added that we were thus able to reduce the framework of the sphere to two circles, the equatorial circle

¹ *Op. cit.*

and one vertical circle, the latter interrupted below to make room for the body of the subject.

In previous experiments upon auditory localization the subject was seated with the center of his head (the intersection of the visual axis with the line joining the two ears and named the auditory axis) in the center of the sphere. But since our subject was monaural it was at first thought necessary, in order that all stimuli might reach him with the same intensity, to center his intact ear (the right ear) rather than the head. This position was afterwards abandoned, for reasons to be mentioned later. It was also found convenient to nail a strip of wood to the floor, parallel with the front legs of the chair, and another strip in the same direction across the under side of the chair with the ends projecting. By placing his feet upon the first strip and his hands upon the projecting ends of the second, the subject could keep himself informed of the position of his body, in reference to which his localization was made. Without these aids his sense of bodily position seemed sometimes uncertain and seemed also to have a disturbing effect upon his localization of sounds.

We began by giving the sound twice for each test, but after the first series it was repeated often six to ten times, until the subject was satisfied with his judgment. The effect of this was simply to secure a normal condition of attention. The subject was then required to name the point from which the sound came, knowing of course the number and location of the points from which it might be given. The sound was given by the experimenter, who closed a circuit by means of a noiseless mercury-contact key. In some of the later experiments, however, it was found convenient to place a contact-key in the hands of the subject, allowing him to give the sound after being informed that the telephone was in position. This method would be recommended for future experiments as securing the best conditions of preparation. To avoid any suggestion of regularity in the order of the points given, the order for each day was determined in advance by shuffling cards bearing the names of the points.

Except where otherwise stated, the electric current used was from three Gonda cells. The current was passed through the primary circuit of an induction coil, in whose secondary circuit

was placed a d'Arsonval galvanometer. The galvanometer enabled us to verify the constancy of the current and the consequent constancy in the intensity of the telephone sound.

The method of notation used by Matsumoto appeared to be the most convenient. In his system the points are designated by significant letters. But we have not included in our system all the points used by him; and since the number of points from which the sound could come has an important relation to the numerical value of the error, we shall not be able to give satisfactory comparisons between his results and our own.

Our system of points was contained in three horizontal circles: an equatorial circle, whose plane passes through the center of the head, a circle 45° above the equatorial circle, and a third 45° below. There were in all sixteen points.

The points on the equatorial circle are designated as follows: *f* (front), the intersection of the visual axis of the subject with the circle in front of the subject; *b* (back), 180° from *f*; *r* (right), the intersection of the auditory axis with the circle on the right; *l* (left), 180° from *r*; *fr*, 45° from *f* and *r*; *br*, 45° from *b* and *r*; *fl*, 45° from *f* and *l*; *bl*, 45° from *b* and *l*.

The points on the upper circle are *fo*, *bo*, *ro*, and *lo*, *o* (over) denoting a point on the upper circle; those on the lower circle are *fu*, *bu*, *ru*, and *lu*, *u* (under) denoting a point on the lower circle.

Fifteen series of experiments were performed.¹ *Series I.* was for the purpose of determining the general characteristics of monaural as compared with binaural localization. A set of 480 experiments was made upon the monaural subject, *A*, and for purposes of comparison under approximately identical conditions a set of 232 was made upon *B*, a binaural subject. The order of each day's experiments was 24 upon *A*, then 24 upon *B*, followed by 24 more upon *A*. The results obtained from *A* are given in Table I., those from *B* in Table II.

The following points of comparison should be noted:

1. In the binaural localizations there were only two instances in which sounds in the median plane and the right and left hemispheres were confused with each other. Matsu-

¹ The series are numbered in the order in which they were performed.

moto's subject made no errors of this kind. But 72 such errors are recorded for *A*, all of which, however, are confusions between the median plane and one of the two hemispheres; in no case are the hemispheres confused with each other.

2. The number of *A*'s correct judgments is 227 out of 480

TABLE I.

Position of sound	Direction in which the sound is perceived to lie.															No. given.
	f	fo	bo	b	bu	fu	fl	lo	bl	lu	l	fr	ro	br	ru	r
f	17	6		2	1	1								3		30
fo		3	5	4								1	3	10		4
bo			20										2	5		3
b			1	25										4		
bu				1	28				1							
fu				18	2	1	1							7		1
fl			1	14	2		5	1	7							
lo			3	2				9	15		1					
bl								6	1	3	20					
lu								1	12	2	15					
l							1	2	2		25					
fr												10	13			7
ro			2		1								14	6	1	6
br				1									1	22		6
ru					1									4	23	2
r														8		22
Total																480

NOTE.—Heavy faced figures indicate right cases. Figures outside the larger squares indicate confusions of middle and right and left.

judgments, or 47.3%. *B*'s correct judgments were 168 out of 232 judgments, or 72.4%.

It will be of some interest to compare with these figures the results obtained by Matsumoto, though, as we have already noted, the difference in the number of points from which choices may be made renders the two results not exactly comparable; for the

points common to his system and ours he obtained out of 800 trials 483 right cases, or 60.4%.

3. The distribution of right judgments for *A* is: median plane 94, left hemisphere 42, right hemisphere 91. Noting that the median plane contains 6 points as against 5 in each hemi-

TABLE II.

Position of sound	Direction in which the sound is perceived to lie.																No. given.
	f	fo	bo	b	bu	fu	fl	lo	bl	lu	l	fr	ro	br	ru	r	
f	12	10															22
fo	1	15															16
bo		7	6														13
b				16	1												17
bu				7	15												22
fu		1	7	5	9	3											25
fl							12	4									16
lo								7			1						8
bl								3	10		1						14
lu									1	9							10
l								1			15						16
fr												12	1			1	14
ro													10				10
br				1										11			12
ru					1										7		8
r														1		8	9
																Total	232

NOTE.—Heavy faced type shows right cases. Figures outside the larger squares indicate transpositions of middle and right and left.

sphere, the ratio of right judgments is as follows: middle 15.7, left 8.4, right 18.2; that is, about half as many right cases occur in the left hemisphere as in either the middle or right. It is to be remembered that the intact ear was on the right. The distribution of right cases for *B* was as follows: 58% of those

in the middle plane, 91 % of those on the left, and 83% of those on the right.

4. The points most often confused with each other were, for *A*, as follows: *l* and *bl* 22 (times), *lo* and *bl* 21, *b* and *fu* 18, *bl* and *lu* 15, *lu* and *l* 15, *fl* and *b* 14, *fr* and *ro* 13, *fo* and *br* 10. For *B* such points were: *f* and *fo* 11, *fu* and *bu* 9, *bu* and *b* 8, *fo* and *bo* 7. It should be noted that *B*'s chief confusions are between points in the median plane, while those of *A* are distributed generally. Since the number of experiments upon the two subjects was unequal, a numerical comparison is not intended; the figures are given merely to show the most important confusions of each subject in order of prominence.

5. These confusions may be further classified as follows: Transpositions forward, *A* 29 (times), *B* 9; transpositions backward, *A* 84, *B* 26. The tendency of both was to locate sounds backward rather than forward of their true position.

6. The following shows the number of errors, classified according to amount of error (disregarding direction). It should be noted that, in our method, the least ascertainable error was 45°. This undoubtedly over-emphasizes the actual error; but the only means of overcoming the difficulty promised more serious complications and was therefore disregarded.

	45°	90°	120°	135°	180°
<i>A</i>	164	26	21	40	2
<i>B</i>	35	17		5	7

The following shows the same, classified according to percentage of the whole amount of error:

	45°	90°	120°	135°	180°
<i>A</i>	64.8	10.3	8.3	15.8	.8
<i>B</i>	54.7	26.6		7.8	10.9

Series II. was performed in order to show the effect of practice. It seemed clear (the subject being in ignorance of the results obtained from himself) that *A* had improved rapidly in accuracy during the progress of Series I. A second series, of 271 experiments, was then given to ascertain the extent of this improvement. For convenience, five points (*bu*, *l*, *br*, *ru*, and *r*) which had already shown a large percentage of correct

cases were omitted in Series II. These points gave in Series I. 120 right and 30 wrong cases. Subtracting these amounts from the totals we have, for the remaining 11 points, 107 right and 223 wrong. The results for these points in Series II. were 139 right and 132 wrong, the number of experiments being about evenly distributed among the different points. A comparison of the two series shows, then, for *A*: in the first series 32.4% right, 67.6% wrong; in Series II., 51.3% right, 48.7% wrong. The distribution and general character of the errors was about the same as in Series I. No further experiments were made upon *B*.

Series III. and IV.—Having ascertained that *A*'s capacity for localization was in general not greatly inferior to that of binaural subjects, it became our object to determine, if possible, just what his data for localization were. It was suggested that he might be guided by cutaneous sensations from his head and neck. Accordingly, two series of experiments were performed in the endeavor to eliminate this factor. The head and neck were covered with a camera-cloth, in which a slit had been made to allow the right ear to protrude. In Series III. the camera-cloth was bound loosely to the head by a strap passed across the forehead and around the head. The results of this series appeared at first to give distinctly positive information. The number of right cases was only 109 out of 318 experiments, and not only were the hemispheres confused with the median plane, but left was a number of times transposed to right. The possibility remained, however, that the transpositions and other errors were due to the cutting off of partial tones, on which basis, perhaps, the localization was made, by the loose folds of the camera-cloth. Accordingly, another series (IV.) was tried, this time with the camera-cloth bound close to the head and face by means of straps passed around the head in three directions. The ratio of right cases (158 out of 310, or 51%) and the nature of the errors were neither of them materially different from those in series II. It seems probable, then, that cutaneous sensations constituted a small part, if any, in the data for localization, though it is necessarily uncertain how far the possible effects of the sound waves were checked by the camera-cloth.

It seems fairly certain, however, that the strong cutaneous stimulation afforded by the contact of the cloth with the skin must have overpowered any effects due to the sound waves alone.

In this connection we should mention a later series (IX.), which was performed with the same end in view. Both ears were fully closed with oily putty as far as the outer rim of the pinnae. The battery power was increased from three to five cells. 57 positions were then given, about evenly distributed among *f*, *b*, *r*, *l*. The only noticeable difference from the normal was the almost universal transposition of *f* to *b*.¹ Otherwise the localizations did not seem to be seriously affected. The net result of these three series was thus merely negative. It is possible, however, that interesting results in this direction might still be obtained from a subject absolutely deaf in both ears.

Series V.—A reference to Series I. and II. shows that sounds in the median plane were transposed frequently to the right but practically never to the left. The subject, *A*, who remained in ignorance of the results, also remarked that sounds which were (correctly) localized as *f* and *fl* appeared to come from a point somewhat to the right of the point which, from his knowledge of the system of points, he judged to be their true position. These facts seemed to indicate that he localized a sound with reference to his head rather than his ear. Accordingly, a series was tried in which the center of the head was located at the center of the sphere. The results are given in Table III.

Compared with Series I. and II., the following facts should be noted :

1. There were only 12 cases of confusion between the median plane and the hemispheres, as compared with 72 in Series I. and 33 in Series II. Comparing the number of experiments with Series I., there should be 48 such cases; with Series II., there should be 39. We have to do here undoubtedly in some measure with continued practice effects. It is, however, extremely improbable that practice is wholly accountable for the result.

¹ Münsterberg (*op. cit.*) using a partial filling of wax for the external meatus and conch, decided that the pinnae were chiefly important in the localization of sounds from in front. Compare also note above on page 226.

It seems more reasonable to suppose that the conditions of this series were intrinsically more favorable for monaural localization.

2. The number of correct judgments is 240 out of 322, or 75%, as compared with 47.3% in Series I., 51.3% in Series II., 60.4%

TABLE III.

Position of sound.	Direction in which the sound is perceived to lie.																No. given.	
	f	fo	bo	b	bu	fu	fl	lo	bl	lu	l	fr	ro	br	ru	r		
f	20																20	
fo		16		7										1			24	
bo			18													2	20	
b				19										1			20	
bu					19	1											20	
fu	2			4		10								3			19	
fl						1	16		3								20	
lo		1						19									20	
bl						1	17		0		2						20	
lu									4	11	5						20	
l							8	2	2		7						19	
fr												19	1				20	
ro													17		3		20	
br	2													9		9	20	
ru															20		20	
r																20	20	
																	Total	322

NOTE.—Heavy faced type indicates right cases. Figures outside the larger squares indicate transpositions of the middle and right and left.

for Matsumoto's subject, and 72.4% for *B*. Taken as it stands the percentage is thus larger than any other recorded.

3. The distribution of right cases is: median plane, 102; right hemisphere, 85; left hemisphere, 53. Noting again that the number of points in the middle was 6, as compared to 5 in each hemisphere, the ratio is: median 17, right 17, left 11.

The greater proportion of error is naturally, as at the beginning, on the side of the deaf ear.

4. The main confusions are between *fl* and *bl*, 20; *fl* and *l*, 8; *br* and *r*, 9; *fo* and *b*, 7.

5. The most uncertain of all positions is *bl*, for which there are no right judgments. For some reason *l*, which was easily localized in Series I. and II., now partakes of the general uncertainty of all localizations in the left hemisphere. In this connection it should be noticed that *lu*, which has hitherto been very uncertain, now shows a fair percentage of right cases, the reason for which seemed to be that, in the first position of the body, *lu* was damped by the proximity of the subject's sleeve. This fact seems to have had a marked effect upon the apparent position of the sound. *fu*, which was close to the knees, was not at any time clearly identified, and was the only point seriously uncertain for *B*. These considerations point to the quality of the sound as a factor in localization.

Series VI. and VII. were merely confirmatory. Series VI. was for the purpose of eliminating as possible factors in localization the modifications of the sound due to the walls of the room and objects in the room. The subject had previously faced north; he now faced successively south, west and east, and in each position was given forty sounds, distributed equally among the four sound-positions most accurately localized (*f*, *r*, *b*, *bu*) and the four least accurately localized (*fu*, *l*, *bl*, *br*). A similar procedure was followed in Series VII., with the exception that here the variable factor was the intensity of the sound. The current had been furnished hitherto by three cells. In Series VII. the strength of the current was varied—two, three and five cells being used. Forty sounds were given with each arrangement of the cells—not, however, in separate groups, but in irregular order in one group, the subject not being informed of the strength of the current. No departure from the normal occurred in either series. This would again seem to indicate that the quality of the sounds, rather than the intensity of the fundamental tone in the sounds, was the important factor in the localization.

In *Series VIII.* we attempted to ascertain the location of the

eight points in the equatorial circle in the subjective auditory field of the subject *A*. Starting from a point on the equatorial circle about 45° from the point whose subjective location was required, the telephone was moved slowly toward the latter point, until the subject declared that it had been reached. The distance between the subjective and objective location of the point was then measured. Five measurements were made from each side of the point, and the mean of the averages of the two sets of five was chosen as the subjective location of the point. The locations were found to be as follows: *f*, 8.2° toward *r*;

The dotted lines intersecting the outer circle indicate the places at which the subject localized the cardinal points on the equatorial circle. (For explanation, see Series VIII.)

The arcs of the incomplete inner circle indicate roughly the limits of variation in the subjective field of the sounds localized at the several cardinal points opposite the arcs. Thus, a sound localized at 90° was almost invariably felt as coming from a point somewhat back of 90° , although the amount of this subjective displacement varied, as the line shows.

fr, 2.6° toward *f*; *r*, 9.4° toward *f*; *br*, 2.2° toward *b*; *b* at *b*; *bl*, 12.5° toward *b*; *l*, 16° toward *f*; *fl*, 10.1° toward *f*. The mean variations for the sets of five were, in degrees, as follows: at *f* 2.2; at *fr* 2.5; at *r* 2.7; at *br* 2.7; at *b* 3.4; at *bl* 4.8; at *l* 2.6; at *fl* 1.7.

The accompanying diagram illustrates the facts brought out in this series, together with certain other peculiarities of the subjective field of auditory localization.

Series IX. has already been adequately described.

The remaining six series were for the purpose of testing definitely the hypothesis that *A*'s localization of sounds rested upon the modification, through the shape of the ear, head or body, of particular partial tones for particular directions. The hypothesis will be stated more fully later. Assuming it to be true, we should expect the accuracy of localization to vary with the complexity of the sound, with the pitch, and possibly with the distance. Accordingly, the remainder of the experiments was devoted to testing these points.

In *Series X.* we used the Galton whistle in place of the telephone. The tone employed was of approximately 10,700 vibrations per second. 92 positions were given, of which 29, or 31.5%, were localized correctly. From the median plane 3 were transposed to the left, 8 to the right; from the left 8 were transposed to the median plane, 3 to the right; from the right 3 were transposed to the median plane.

In *Series XI.* a tone of approximately 5,000 vibrations per second was used. 62 positions of the sound were given, of which 14, or 22.6%, were localized correctly. The transpositions were: from middle to left 6, to right 9; from left to middle 2; from right to middle 3.

In *Series XII.* the whistle tone was lowered to approximately 2,500 vibrations per second. 46 positions were given, of which 32, or 70%, were correctly localized; no new transpositions appeared.

The tone of the Galton whistle is not pure, but save in the case of the deeper tones which it is capable of giving, *e. g.*, that used in *Series XII.*, the partial tones are weak and very high. The complex nature of the tone is, therefore, not easily

detected. We should expect, then, that the localizations of its higher tones would be more uncertain than those of the telephone. A reference to Series X. and XI. shows this to be the fact. Comparison may be made with either Series I. or V.

We should expect Series X. to show a smaller percentage of correct localizations than Series XI., as qualitative differences ought to be more difficult of detection, because the partial tones should be higher and weaker. The percentage of correct localizations is, however, slightly in favor of Series X. This fact is more than offset by the nature of the confusions and transpositions which are encountered in Series X. The hemispheres are confused with each other, as well as with the median plane. This does not occur in Series XI. The total number of tests is too small to warrant great insistence upon this difference. But the marked difference between Series X. and XI. on the one hand and Series XII. on the other suggests strikingly the effect of using sounds whose partial tones are weak and very high, as compared with those possessing partials which are relatively strong and well within the limits of audition. Series XII. shows almost as good results as Series V.

In *Series XIII.* we tried to discover whether the peculiar quality of the sound supposed to be the basis of its localization was a function of its distance from the ear. Accordingly, the eight equatorial positions were given each four times at a point thirty inches beyond the surface of the sphere, the telephone being used as the source of sound. The results were the same, however, as the normal results given in Series V. We can hardly conclude from this that greater variations of distance would be equally ineffective.

In *Series XIV.* the sound was given with a tuning-fork of 1,024 vibrations. The fork was placed at the surface of the sphere and only the eight equatorial positions were given. 42 sounds were given, of which 6, or 14.3 %, were correctly localized; the latter were one each at *f*, *fr*, *l* and *fl*, and two at *r*. In 10 cases the subject was unable to localize the sound at all.

In *Series XV.* we substituted a fork of 512 vibrations. 24 sounds were given, of which none were correctly localized;

20 were incorrectly localized and 4 could not be localized. Similar results were obtained with a fork of 256 vibrations.

The tuning-fork tones of Series XIV. and XV. are theoretically pure tones. As a matter of fact it is difficult to avoid, in striking the forks, some slight production of partial tones. This is more noticeable with the 1,024 fork than with the 512 and 256. For the two lower forks localization is clearly out of the question. In the case of the 1,024 fork, also, it is essentially impossible. The number of localizations correctly made in the latter case is somewhat above the number to be expected by the laws of chance, but it is to be added that the subjective attitude even in these correct cases was one of extreme uncertainty, and the total number of tests made is too small to permit of attaching much importance to the operations of mere chance. With the tuning-forks, and in less degree with all of the sounds we used, the change in position is accompanied by slight apparent changes in pitch. In the case of the telephone and whistle tests this change is partially, at least, incidental to the modification of the partial tones. In the case of the tuning-forks the cause is probably of another character, but whatever its nature it is inadequate to afford reliable localizations under the conditions we have studied.

III.

Taking account of all the facts brought out by the tests, we reach the following conclusions:

1. The differences in the localizing capacity for complex sounds in binaural and monaural hearing are, so far as concerns these subjects, interpretable as chiefly differences in the magnitude of the difference limen for locality, rather than as absolute differences in the kind of localizing process involved. In monaural hearing the localization of sounds is by no means a matter of chance. On the side of the intact ear the localizations are in no sense seriously defective, and the distinction between front and back may be made in a manner superior to that of binaural hearing. (Cf. Series I., II. and V.) In the region opposite the deaf ear the localizations are extremely uncertain, but

elsewhere the errors met with are simply slight exaggerations of those made in binaural hearing.

It is not intended to imply in this statement that monaural localization is generally as prompt as binaural, nor that it is as accurate in its capacities for dealing with new and strange sounds. (Compare Series I. with Series II. and V. showing practice effects.) But practically all complex sounds are localized with a reasonable degree of accuracy, subject to the exceptions mentioned in connection with Series X., XI., XII., even upon a first hearing, and a little experience with the sound, familiarizing the subject with its quality changes, leads to such accuracy in its localization as is exhibited in Series V.

2. The experiments objectively considered amply sustain the introspection of the subject in pointing to qualitative differences in the sounds coming from different directions, as the basis of the localizations. This was explicitly commented upon by the subject very early in the course of the experimentation.

Sounds which are complex in nature undoubtedly undergo modification through the damping and reinforcing of their partial tones by the *pinnæ*, the external meatus and the head, in a manner which must vary somewhat regularly with variations in the spatial position of the object from which the sound emanates. When the changes in these objective positions are small, the corresponding changes in the quality of the sounds are ordinarily minute. But there is undoubtedly a general parallelism between the two series of events, and there is no reason why these variations should not be employed for auditory localizations as genuinely in monaural hearing as in binaural hearing, albeit necessarily with less of accuracy in some portions of the field.

The one region throughout which in monaural hearing such differences in the quality of sounds would be absent, or seriously ambiguous, is that immediately opposite the defective ear. In this case the whole of the head is interposed between the source of the sound and the intact ear. Sounds are much weakened in absolute intensity by this circumstance, as anyone may speedily convince himself, and the damping of the partial tones, upon which depend the qualitative peculiarities of sounds,

is essentially similar for all points in the region.¹ The extreme uncertainty and the persistent confusions which we encounter in monaural localization throughout this region are then precisely what we should anticipate, provided the qualitative differences of sounds constitute the basis of such localization.

Certainly it is striking that those sounds are most accurately and most promptly localized, which contain a considerable number of partial tones well within the limits of audition. The more nearly the sounds approach pure tones, the more inaccurate the localization. This is true regardless of the absolute pitch. Genuinely pure tones are essentially unlocalizable in monaural hearing. Such localization of these tones as is possible in binaural hearing is, therefore, probably referable to the intensity factor.² It is to be remembered that the deeper tones which we employed are practically pure. Most of the higher tones possess a few overtones. The sounds most accurately localized were always those in which qualitative differences were noticed and in which modification of partial tones was physically possible under the conditions.

It is assumed, in this statement, that the effects of experience, involving especially motor and visual processes, enter indispensably into acts of auditory localization. With adults, these intensive-qualitative auditory differences, to which we have made constant reference, simply furnish the relatively fixed psychic contents, whose spatial relations can then be learned. The process of giving to these elements values in the general visual-tactual-kinæsthetic space world is definitely the business of experience. How far some of these motor processes may be connected in a genuinely reflex and hereditary way with auditory stimulations is not a matter which we can at present discuss.

¹ The failure of some persons deaf in one ear to localize with any considerable degree of accuracy may be due to any one of a number of reasons, no one of which would impeach the validity of our interpretation.

² This radical defect in the monaural localization of pure tones furnishes a serious difficulty to those theories which refer auditory localization to the reflex action of the semi-circular canals. One can conceive of reasons why, as in binaural hearing, such localization should be uncertain and relatively inaccurate. But it is not so easy to explain how in monaural localization the process should work fairly well for many sounds, only to break down hopelessly upon pure tones.

Our examination of monaural hearing suggests, however, the extent to which one set of auditory symbols, *i. e.*, qualitative peculiarities in sounds, may serve for localizations. It substantiates indirectly, therefore, those theories of binaural localization which emphasize quality changes as more important for consciousness than mere variations in intensity.

It may be suggested that the changes in the quality of sounds, which seem to furnish the basis of monaural localization, are in one particular seriously ambiguous. Changes in distance, as well as changes in direction, are frequent causes of an apparent change in auditory quality. This being true, it would seem to indicate that in monaural hearing these two changes would often be confused with each other.

Undoubtedly variations in the quality of sounds may be produced by changes of either kind. But it is by no means certain that the effects upon the quality of the two kinds of change are sufficiently similar to be often confusing. Certainly our tests in Series XIII., although by no means conclusive, suggest strongly the ability to distinguish such qualitative-intensive differences as are due to changes in direction, from such as are due to changes of distance.

3. The presence of eye-reflexes was often very marked, and the final localization was frequently made on the basis of a seeming correspondence between the eye-strains and the supposed direction of the sound. This statement leaves wholly untouched the physiological basis of the eye-movements. It may be added, however, that the subject is rather a vivid visualizer and almost always thinks of spatial relations in visual form.

4. There is no good evidence for supposing that cutaneous sensations played any part in the localizations.