Theories of Hearing*

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RIVALRY still exists between the theories of hearing, because the small size, the delicacy, and the inaccessibility of the internal ear make direct observation and experimentation wellnigh impossible. Among the rival theories are the telephone theory, the modified telephone theory of Boring, the modified telephone theory of Watt, the volley theory of Wever and Bray, the pattern theory of Ewald, the stationary wave theory, and the resonance theory. At the present day, controversy principally centres round the resonance theory and some form of telephone theory.

THE TELEPHONE THEORY

According to the telephone theory, the ear behaves like a microphone. Variations of air pressure in the ears, at the frequencies of sound emitted by the source, are followed by the passage of impulses up the auditory nerve fibres to the brain. Like the electric currents in a telephone wire, these nerve impulses are controlled by the frequencies, intensities, and the phases of the incoming sound waves. The temporal lobe of the brain, on receiving these nerve impulses, interprets suitably the changes in pitch and quality which are heard, and assigns them to the musical instruments which are being employed.

The telephone theory encounters the following difficulty: experiment shows that the ear can hear frequencies up to about 15,000 vibrations per second. A telephone circuit transmitting these high frequencies would undergo 15,000 fluctuations in voltage per second. The ear, if it were behaving like a telephone, should therefore send up the fibres of the auditory nerve 15,000 impulses per second. But experiment shows that the highest frequency at which mammalian nerve fibres can transmit impulses is about 1000 per second. A modification of the telephone theory, called 'the volley' theory, meets this difficulty by assuming that a suitable co-ordinating mechanism exists in the internal ear. By means of this mechanism the auditory nerve fibres are divided into groups and each group in turn is called on to transmit an impulse. If there were 15 such groups, a frequency of 15,000 vibrations per second could be conveyed to the brain by nerve fibres which individually can only convey 1000 vibrations per second.

THE RESONANCE THEORY

According to the resonance theory, the ear contains a number of tuned structures, the natural periods of vibration of which correspond to the range of audible frequencies. Separate nerve fibres connect the sensory organs on these 'resonators' with different parts of the temporal lobe of the brain. In consequence, when sounds of one frequency are received, and one group of resonators

vibrates, the sense organs of these resonators are stimulated and their nerve fibres convey impulses to one part of the temporal lobe. Sound waves of other frequencies will cause different groups of resonators to vibrate, and different parts of the temporal lobe will thus receive nerve impulses.

The resonance theory encounters the following difficulty: the vibrating structures in the ear have lengths of roughly half a millimetre, and the lowest audible frequency is approximately 20 vibrations per second. It is at first sight difficult to see how it is possible for such very short structures to perform vibrations in resonance to such low frequencies.

The formula for the fundamental frequency of vibration of a stretched string is as follows:

$$\text{frequency} = \frac{1}{2 \text{ length}} \times \sqrt{\frac{\text{tension}}{\text{mass per unit length}}}$$

If, therefore, tension is suitably decreased at the same time as length, then frequency remains the same. It is therefore possible to have a fibre 0.5 mm. in length possessing a natural frequency of 20 vibrations per second, provided that the tension has a suitable value. The vibrating structures of the ear satisfy the required conditions.

EXPERIMENTAL EVIDENCE IN FAVOUR OF RESONANCE

Much experimental work has accumulated during the last few years which is in favour of the resonance hypothesis and against the telephone hypothesis.

(1) When by surgical interference a limited part of the internal ear is damaged, not only does deafness over a narrow range of frequencies result, but also the frequencies concerned correspond with the part of the internal ear which has been damaged. That is to say, if the damaged fibres are short, then high notes are involved; if, on the other hand, the damaged fibres are long, then low notes are involved.

(2) Boilermakers, in course of time, acquire deafness to high notes. Microscopic examination after death shows that the short fibres of the internal ear have been pathologically affected. Also, when animals are subjected for considerable periods of time to loud sustained musical tones, they become deaf to the musical tone to which they have been subjected. A microscopic examination of their internal ears after death shows that the fibres affected correspond approximately in length to the frequency of the tone to which the experimental deafness has been produced.

(3) When a musical tone, transmitted by a telephone circuit, is suddenly changed in phase by a half-cycle, the voltage fluctuations in the circuit continue almost without interruption.

When a musical tone, which is causing a tuned structure to perform resonant vibrations, is suddenly changed in phase by a half-cycle, the

* Friday evening discourse at the Royal Institution, delivered on April 29.

vibrations of the tuned structure are first arrested and are then re-established. On performing a similar experiment with the human ear, just after the change of phase the musical note is heard to undergo a short interruption, that is, the ear behaves as if it contained resonators, and unlike a telephone.

(4) When a musical tone is interrupted for short periods of time, similar interruptions can be identified in a telephone circuit which is excited by the sound. When a musical tone, which is causing a tuned structure to perform resonant vibrations, is interrupted for a short period of time, the vibrations of the tuned circuit are found to continue with only a small diminution in amplitude. On performing a similar experiment with the ear, it is found that short interruptions cannot be detected; hence the ear behaves as if it contained resonators, and unlike a telephone.

(5) When two musical tones differing considerably in frequency, for example, 200 v. per sec. and 250 v. per sec., are sounded simultaneously into a telephone, the voltage fluctuations in its circuit are found to correspond to a single frequency of 225 v. per sec. with periodic increases and decreases of amplitude (beats) occurring 50 times a second. When the above two tones are caused to set up vibrations in a graduated series of resonators, two separate groups of resonators are found to be set into vibration, one corresponding to 200 v. per sec., the other corresponding to 250 v. per sec. A careful examination of the groups shows that neither of them is exhibiting appreciable beats. On performing the experiments with the ear, the two separate tones of 200 v. per sec. and 250 v. per sec. are heard and no beats are to be observed; hence the ear behaves as if it contained resonators, and unlike a telephone.

(6) When two musical tones having frequencies in the ratio of 1 to 3 are sounded simultaneously, the voltage fluctuations in a telephone circuit excited by them are found to be greatly affected by the relative phases between the two tones. In one phase relationship a single sharp peak curve is produced. In another phase relationship a double hump curve is produced. When the above two tones are caused to set up vibrations in a graduated series of resonators, two groups of resonators are found to be set into vibration, one group for each tone. The careful examination of the groups shows that neither their frequency nor amplitude is affected appreciably by changing the relative phases of the two tones. On performing the experiment with the ear, it is found that changing the relative phases of the tones has no effect on the sounds which are produced; that is, the ear behaves in accordance with the resonance theory and contrary to the telephone theory.

(7) It is well known that resonators exhibit the properties of selectivity (sharpness of resonance) and persistence, and that both these properties are related to the frictional losses to which the resonators are subject. In consequence of this, when different degrees of selectivity are multiplied by corresponding degrees of persistence a constant

value is obtained, as is shown in the following table:

<i>S</i> (selectivity).	<i>P</i> (persistence).	<i>S</i> × <i>P</i> .
1.5	40	60
2.0	30	60
3.0	20	60
4.0	15	60
6.0	10	60

(Selectivity in the above table is the percentage difference of frequency causing one-tenth the amplitude of that caused by the intune frequency at the same energy level. Persistence is the number of vibrations which correspond to the time required for the amplitude to be reduced to one-tenth its initial value.)

Now, the selectivity of a graduated series of resonators can be ascertained experimentally by finding the smallest difference of frequency which causes beats owing to the overlap of the two vibrating groups of resonators. The persistence of a series of resonators can be ascertained experimentally by finding the duration of the longest interruption in the incoming sound energy which produces no observable decrease in amplitude. Both these methods of research are applicable to the ear, and the table below gives the values I obtained. The last column shows that their product gives a reasonably constant value, as should be the case if the ear resonators are of the kind familiar to the physicist.

Tone.	<i>S</i> .	<i>P</i> .	<i>S</i> × <i>P</i> .
128	12.7	1.78	22.6
256	10.0	2.06	20.6
326	9.45	2.19	20.7
384	9.07	2.18	19.75
512	8.45	2.37	20.0
640	8.15	2.54	20.65
760	7.82	2.68	20.95
1024	7.22	3.01	21.70

REPLIES TO OBJECTIONS TO THE RESONANCE THEORY

(1) In a piano the wires are all separated from one another and are therefore free to vibrate individually. It is not difficult therefore to picture a small group of wires, or even a single wire, being set into resonant vibration. In the internal ear, on the other hand, the resonating fibres are seen under the microscope to be attached sideways to one another. How is it that these attachments do not impede or even stop resonant vibrations, or at the very least produce an irregular jangling?

In replying to this question, two points require emphasis; first, that when a group of resonators is being set into vibration by incoming sounds, those above and those below the frequency of the resonator which is strictly in tune with that of the sound are performing what are aptly called 'forced vibrations'. They do not perform vibrations at their own natural frequency, but vibrate at the frequency of the incoming sound energy. Thus, suppose a group of wires of a piano to be set into resonant vibration by a strong source having a frequency of 200 vibrations per second. Then, a stroboscopic examination of the vibrating wires should show that those on one side of the intune resonator are all moving towards or away from the observer at the same time.

Secondly, the number of fibres of the internal ear set into forced vibration by a pure source of sound is much more numerous than is usually supposed. If, having ascertained the fibre strictly 'in tune' with the musical tone, we count sixty fibres above it in pitch, on examining this fibre we should find that it is performing vibrations with an amplitude which is approximately one-tenth the amplitude of the 'intune' fibre. The sixtieth fibre below the intune one is also performing vibrations with an amplitude of one-tenth the intune one. Since so many fibres are affected, the difference in amplitude between one fibre and its next-door neighbours is very small; calculations show that they nowhere exceed 5 or 6 per cent. The attachments of the fibres to one another should therefore not markedly impede their vibration, and are therefore not incompatible with the resonance theory.

(2) So long as the incoming vibrational energy continues, resonators continue to vibrate; when this energy ceases, they gradually come to rest in an exponential manner. If the ear contained resonators, on the cessation of a musical tone we ought to be able to hear a gradual diminution of loudness. Everyday experience shows us, however, that silence appears to follow the cessation of musical tones almost immediately, and this is incompatible with the resonance theory. The explanation of this objection is as follows: If we know the threshold of stimulation of the sense organs attached to the fibres in the internal ear, and if we know the degree of persistence of the ear, we can readily calculate the time taken for the vibrations of the fibres to be reduced until 'silence' is reached. The values thus obtained for notes of medium loudness are given in the following table:

Tone.	Time in Seconds for Termination of Hearing.
128	0.057
256	0.036
512	0.021
1024	0.012

We see that these times are very short. Even for a tone of 128 vibrations a second, the time of the termination of hearing is less than one-seventeenth of a second. Our experiences, therefore, are not incompatible with the resonance theory.

(3) Pathological changes in the internal ear are sometimes found to produce deafness to one or more groups of frequencies. Whereas most tones, both high and low, are heard in a normal manner, there is deafness to certain intermediate ranges of frequency. It is often found that a frequency inside this range can be correctly perceived if its intensity be much increased. This finding is held to be incompatible to the resonance theory, on the following grounds: Suppose a certain number of fibres of the internal ear to be destroyed, then it is clear that the ear will be deaf to tones corresponding in frequency to the damaged fibres. If now a tone of sufficient intensity be sounded, which corresponds in frequency to the centre of the damaged region, normal fibres at the edges of the deaf region should be caused to perform vibrations. Provided that the stimulating tone be loud enough, the forced vibra-

tions should have sufficient amplitude to stimulate their respective sensory end organs. The individual should now hear one or more musical tones which correspond to the frequencies of these normal fibres. But experiment shows that what he does hear is a tone which corresponds to the frequency of the tone which is being sounded.

An example may make matters clearer. Suppose a man to be deaf to frequencies of from 200 to 240 vibrations per second, owing to complete destruction of the fibres which correspond to this region. Then on sounding a tone of 220 vibrations a second of ordinary intensity, nothing is heard by the affected ear. On sufficiently increasing the intensity of the sound, however, there should be, according to the resonance theory, forced vibrations on the part of the normal fibres just below 200 vibrations per second and just above 240 vibrations per second, and therefore the individual should hear two musical tones corresponding to these frequencies. Experiment shows, however, that what he does hear is a single musical tone corresponding to 200 vibrations per second, a result which, it is claimed, is incompatible with the resonance theory.

The reply to this objection is that its supposed pathological basis is unsound. Regions of deafness are not due to clean-cut destruction of certain fibres leaving neighbouring fibres intact, but rather to localised adhesions and exudates interfering with the normal vibrations of the fibres. In consequence, a tone of normal intensity sets the affected fibres into such feeble vibration that their sense organs receive insufficient stimulation. A more intense tone, on the other hand, may cause sufficient amplitude of vibration for the stimulating tone to be recognised. The behaviour of an individual with islands of deafness is not, therefore, incompatible with the resonance theory.

(4) It is found by experiment that a dog in which a limited number of fibres of the internal ear has been destroyed by a drill, exhibits afterwards deafness to a very small range of frequencies. Now, according to the resonance theory, many fibres are affected by a single frequency, and therefore deafness to a considerable range of frequencies should occur. Since this is not found to be the case, this experimental result is claimed to be incompatible with the resonance theory.

The reply to this objection is as follows: Suppose the part of the internal ear affected by the drill to be one millimetre in width. Then it is found by calculation that approximately 350 fibres would be destroyed. Now, we have evidence that one musical tone affects approximately 200 fibres, so that it is clear that the deaf region would correspond to the difference between these two values, namely, 150 fibres only. These would correspond to a piece of the cochlear 0.4 mm. in length, a length which is less than half that affected by the drill. The experimental finding that the deaf region is narrower than the destroyed region is in agreement with the resonance theory.

(5) In recent experimental investigations on the auditory nerves, Wever and Bray have detected

electric currents which correspond in frequency and phase to the sound waves falling on the ear. This would be the case if the auditory nerve were behaving like a telephone circuit, and if the internal ear was acting like a microphone. This evidence, which is in favour of the telephone theory, is at variance with the resonance theory. Now, Adrian, who has recently repeated Wever and Bray's experiment, found that freezing or crushing the auditory nerve, or putting novocaine on it, did not stop the effect, which cannot, therefore, be due to the passage of nerve impulses along it.

It would seem that the phenomenon, interesting as it is, has nothing directly to do with the behaviour of the internal ear, so far as normal hearing is concerned. There would appear to be no justification at the present time in claiming these experiments as being in agreement with, or in contradiction to, the various theories of hearing.

(6) According to the resonance theory, a great many fibres are set into vibration by a single pure tone, and fibres at the edges of the group differ from the centre one, which is 'in tune' with the incoming vibrations, by roughly a semitone. Why, then, do we not hear a dissonant noise when a single frequency falls on our ears? Gray has answered this objection by supposing that in some way the sense organs attached to the fibres are able to detect the fibre which is performing the maximum amplitude of vibration; and that the brain, receiving impulses of a special kind up the nerves connected with this fibre, is able selectively to receive the frequency corresponding to this fibre and to ignore the impulses from all the other more outlying fibres which are set into vibration by the tone.

Not only is it extremely difficult to see how a suitable physiological mechanism could be devised to do this, but also it would place the ear in a completely different category from that of vision and touch. In vision, we meet a corresponding phenomenon, for a point source of light stimulates not one cone sense organ of the retina but many cones. This effect causes no confusion. We always have seen point sources (for example, stars) that way. We presumably shall continue to do so all our lives. So with hearing. Single pure tones have always set a certain number of fibres into vibration; it is an effect to which we are accustomed. It would seem entirely unnecessary to invoke a special, and unusual, type of mechanism to deal with the phenomenon.

CONCLUSION

When, fourteen years ago, Wrightson published his book, the telephone theory received at his hands an impetus which was just what it required. The resonance theory had fallen into disrepute, the telephone was replacing it, and people were hesitating between the two. Unfortunately for the telephone theory, it was not long before criticisms of Wrightson's book began to accumulate. So serious were these criticisms that Wrightson's views had to be wholly abandoned. Since then, evidence has been accumulating in favour of the resonance theory. Objections to it appear in many cases to be based on erroneous ideas with regard to resonators and sense organs. It would seem, at the present time, that the resonance theory accounts satisfactorily for all the phenomena of hearing, and that no other theory does this.

Royal Society of Canada

ANNUAL MEETING IN OTTAWA

ON May 26-28 the Royal Society of Canada met in the new building of the Canadian National Research Council in Ottawa. Several features of the meeting arose out of the fact that the Society was celebrating its jubilee. Learned societies of Great Britain, France, and the United States sent delegates. The presidential address by Sir Robert Falconer, on the evening of May 26, was an eloquent and instructive survey of the remarkable progress of the intellectual life of Canada during the past half-century, as reflected in the proceedings of its Royal Society and, in fact, dominated by the fellows of the Society. This address and a series of detailed histories of the progress in special fields are assembled in an anniversary volume, entitled "Fifty Years' Retrospect". At the same evening meeting, delegates were received, a diploma was presented to the Prime Minister, Mr. Bennett, and the various medals were awarded, namely: the Flavelle Medal to Dr. J. S. Plaskett for his contributions to astronomy, the Lorne Pierce Medal to Dr. Archibald MacMechan for achievements in literature, and the Tyrrel Medal to Dr. Pierre-Georges Roy for his historical researches.

A new function of the Society appeared in the announcement by the Council of the award of ten fellowships endowed by the Carnegie Institution.

At the meetings of Section 1 (French Literature and History) twenty papers were read, and of Section 2 (English Literature and History) twenty-five papers were read.

The presidential address to Section 3 (Physics, Mathematics, Astronomy, and Chemistry) was delivered by Prof. A. Norman Shaw, who gave an interesting account of the developments in physics during the last fifty years. He paid tribute to the work done by physicists in Canada, dwelling especially on the contributions made at McGill by the late Prof. H. L. Callendar, Lord Rutherford, and by Prof. J. C. McLennan in Toronto. After reviewing the work in physics of the past and present fellows of the Section, he concluded his interesting address with a plea for closer co-operation between science and government with the words: "We await Governments which will devote their major expenditures of effort, time, and money in studying and directing the efficient harvesting and even