XX.

CONTRIBUTIONS FROM THE PHYSICAL LABORATORY OF THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

XXXIX. — ON SOME EXPERIMENTS WITH THE PHONOGRAPH, RELATING TO THE VOWEL THEORY OF HELMHOLTZ.

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THE value of the phonograph as an aid in the study of the theory of vowel tones was recognized almost immediately upon the invention of that instrument, and it was employed for this purpose as early as 1878 by Messrs. Jenkin and Ewing,* and also by Dr. C. J. Blake in connection with one of the present writers. The experiments of the last mentioned observers were designed to aid in the solution of the question whether it is a fact, as assumed by Helmholtz, that each vowel possesses a distinctive character due to the presence of a particular tone or tones, which are the resonance notes of the mouth cavity when shaped for the utterance of the corresponding vowel. The method employed, and the results obtained were described in a letter to *Nature* (Vol. XVIII. p. 93), so that a brief reference to them will suffice.

The plan followed was to speak a vowel into the mouthpiece of the phonograph when the cylinder was revolved at a certain rate, and then to reproduce the tone with a varying rate of revolution, both faster and slower than that used when the record was impressed upon the cylinder. Any particular resonance note, if present, would then have its pitch raised or lowered, and presumably the vowel sound would be correspondingly altered.

This was found to be the case, the vowel apparently changing with change of speed of the cylinder. For example, the vowel ō

* See Nature, Vol. XVII. p. 384; Trans. Roy. Soc. Edinburgh, Vol. XXVIII. p. 745.

changed to *e* on increasing the speed to a rate considerably above that at which the former vowel was impressed upon the recording cylinder, and fell to *â* when the speed of the cylinder was carried considerably below that at which the record was made.* Various other results of the same character were secured.

The accuracy of these results was questioned, but they were shortly afterwards confirmed by A. G. Bell and F. Blake,† and others. The only form of phonograph in existence at that time, however, remarkable as it then seemed to be, was extremely crude and imperfect, the tin-foil employed as a medium for receiving the record not being well fitted to receive and retain the delicate impressions of the sounds of the human voice. Upon the commercial introduction of the modern phonograph of Edison, in which a cylinder of wax replaces the tin-foil, and which leaves little to be desired so far as clearness of articulation is concerned, it appeared to be desirable to repeat the early investigations just referred to, with the improved instrument. After our work was well advanced, our attention was called to investigations in the same direction by Hermann.‡ But his very valuable researches on vowel tones, and their study by the aid of the phonograph, have mostly employed methods other than the one under consideration, and only some general results by this particular method seem to have been published by him. These are in accordance with the observations described in the letter to *Nature* already mentioned.

The method followed in the present series of experiments is identical with that used in the earlier studies referred to. As the cylinder of the modern phonograph is rotated by an electro-motor furnished with a good speed-governor, it was easy to vary the speed within moderately wide limits, and to keep it at a tolerably definite and known rate, which was done in most of our experiments. In some of these, however, only general results were sought for, and no attempt was made to measure the speed.

We proceed to give a detailed description of a few of our more general preliminary experiments, which is followed by a statement in tabular form of the later and more precise observations. In the

* In this paper the sounds of the different vowels are denoted by the conventional signs employed in the Century Dictionary. Certain other signs used are explained later.

† See American Journal of Otology, Vol. I. p. 163.

‡ Cent. f. Physiologie, 1890, Vol. IV. p. 242; Pflüger's Archiv, 1890, Vol. LXXIV. p. 42.

former, we have noted only those sounds which seemed most prominent in the different series.

(1) The vowel ŏ was spoken into the speaking-tube of the phonograph when the cylinder was rotated at the lowest speed at which it was possible to drive it with the governor used, — about one half-revolution per second. The vowel was then reproduced with a gradually increasing speed of the cylinder up to the highest possible speed, — about three and one half revolutions per second. The experiment was repeated several times, and with different observvers. The sounds heard as represented were

ŏ ō ou ü a.

(2) The vowel ŏ was spoken into the mouthpiece at a speed of about one revolution per second. On reproducing it at lower rates down to about one half-revolution per second, the vowel sound was still heard as ŏ, but becoming more and more guttural, until at the lowest speed it sounded like a deep gurgle.

(3) The vowel ō spoken with a moderately low speed of the cylinder, and reproduced with gradually increased speeds from the lowest possible to the highest, gave the following sounds: —

ŏ ō ǭ ou ä a.

(4) The vowel ō was spoken into the instrument at the highest attainable speed, and repeated a number of times, the speed of the cylinder meanwhile being lowered gradually, so that the vowel in question was impressed upon the cylinder at a variety of speeds, from the highest to the lowest. It was then reproduced with gradually increasing speed of the cylinder, beginning with the lowest possible. This procedure was well adapted to give a large number of vowel sounds in succession. The reproduced vowels noted were

ŏ ō ō ou ä a i.

(5) The vowel ō spoken at the lowest possible rate was reproduced at gradually increasing speeds. The sounds heard were

ō ä a e i.

(6) The vowel ō spoken at a rate of about one revolution per second was reproduced at a lower speed as ŏ and at the lowest attainable speed as a very deep guttural ŏ.

(7) The vowel ē spoken with a cylinder speed of about one revo-

lution per second, and reproduced at speeds varying from the lowest to the highest attainable, gave the following sounds :—

ü *ē* *ẹ̄* *i*.

The last mentioned sound was given out only at the extreme upper limit of speed.

(8) The vowel *ē* spoken with a speed of about two revolutions per second was reproduced at a lower speed as *ü*, but at all attainable higher speeds still retained its vowel character as *ē*.

The following tables contain the results of later experiments in which the speed of revolution was measured. Table I. contains results reached when a single vowel was sounded and reproduced at various speeds. The first column contains the serial number of the experiment; the second, the name of the vowel; the third, the rate of revolution of the cylinder of the phonograph when the vowel was spoken into the mouthpiece and its record impressed upon the wax; and the fourth, the vowel sounds observed when the spoken sound was reproduced at various speeds, R_1. The speed is denoted in revolutions per second.

TABLE I.

No.	Vowel Spoken.	R	Vowels reproduced.					
1	*ō*	1	R_1	½	1	2	3	
			Vowel reproduced .	*ö*	*ō*	*ou*	*ou*♯ (almost *ä*♯).	
2	*ō*	1	R_1	½	1	2	3	
			Vowel reproduced .	*ö*	*ō*	*ou*	*ou*♯ (less sharp than in 1).	
3	*ō*	2	R_1	1	2	3	3½	
			Vowel reproduced .	*ö*	*ō*	*ọ̄*	*ou*	
4	*ä*	1	R_1	½	1	3		
			Vowel reproduced .	*ô*	*ä*	*a*		
5	*ä*	3	R_1	3	2	1	½	
			Vowel reproduced .	*ä*	*ô*	*ō*	*ö*	
6	*ä*	2	R_1	½	1	2	3	
			Vowel reproduced .	*ö*	*ô*	*ä*	*a*	
7	*ā*	½	R_1	½	1	2	2½	3
			Vowel reproduced .	*ā*	*ä*	*a*	*e*	*i*
8	*i*	1	R_1	½	1	2		
			Vowel reproduced .	*e*		*i*		

TABLE II.

No.	Vowel Spoken.	R	Vowels reproduced.				
9	ö ō	1	R_1	1	2		
			Vowel reproduced .	ö ō	ō ou		
10	ō ö	1	R_1	1	2		
			Vowel reproduced .	ō ö	ou ō		
11	ē ĕ ō	1	R_1	1	2	3	
			Vowel reproduced .	ē ė ō	è ē ou	ẹ̄ ẹ̄ ä	
12	ē ō ē	1	R_1	1	2	3	
			Vowel reproduced .	ē ō ē	è ou ē	ẹ̄ ou# ẹ̄	
13	ē ö ē	1	R_1	1	2	3	3½
			Vowel reproduced .	ē ö ē	ē ō ē	ẹ̄ a ẹ̄	ẹ̄ a# ẹ̄
14	ō ē ē	1	R_1	1	1½	2	
			Vowel reproduced .	ō ē ē	ou ē ē	ou# ẹ̄ ẹ̄	
15	ō ö ā	1	R_1	1	2	3	
			Vowel reproduced .	ō ö ā	ou ō a	ou# â e	
16	ö ō ā	1	R_1	1	2	3	
			Vowel reproduced .	ö ō ā	ō ou a	ọ̄ ä e	
17	ā ö ō	1	R_1	1	2	3	
			Vowel reproduced .	ā ö ō	a ō ou	a# ọ̄ ou#	
18	ō ē ā ī ö	1	R_1	1	2	3	
			Vowel reproduced .	ō ē ā ī ö	ou ẹ̄ ā# ị̄# ō	ou# ẹ̄ ị̄ a# ọ̄	
19	ō a ī ö ē	1	R_1	1	2	3	
			Vowel reproduced .	ō a ī ö ē	ou a# ị̄ ō ẹ̄	ou# a# ị̄# ọ̄ ẹ̄	
20	ö ō ä e i	1	R_1	1	2	3	
			Vowel reproduced .	ö ō ä e i	ō ou a# ẹ ị	ọ̄ ou# a# ị̄ u#	

In addition to what has already been said as to the conventional signs used by us to indicate the different vowel sounds, it should be stated that in the preceding tables and subsequent pages a # following a vowel indicates a rise in its characteristic note, generally with an accompanying nasal quality. Thus in (1), (2), (12), and elsewhere, the sound denoted by *ou#* is nasal. In (1) it approaches a nasal *ä*. In (13) and elsewhere, the sound denoted by *a#* lies between *a* and *e*, and closely approaches or even passes into the French nasal *in*. The sound *ā#* in (18) approaches *ī*. The sound *ị̄#* in (18) is strongly nasal in quality. The *u#* in (20), however, is not at all nasal, but is a very high *u* with a resonance note much higher than that of *ị̄*.

Several series of experiments were also tried in which a number of vowel sounds in succession were impressed upon the cylinder, and subsequently reproduced at different speeds, — a method which enables one to compare more readily the changes in the various vowels with one another. The results of these comparisons are found in Table II.

A careful comparison of the various changes indicated in the preceding tables will show a close accordance between the results of different experiments. But there will be noticed a few apparent discrepancies. Thus in (15) *ō* rises to *ou♯* and in (16) to *ä*; in (15) *ö* rises to *â*, and in (16) to *ọ̄*, while *ā* rises to *e* in both series. These and such other like results as exist are due chiefly to the fact that it was difficult to measure the speed with any great exactness at the higher rates, or to maintain this speed absolutely uniform, and a slight increase in speed would suffice to change the results as stated in (15) to those of (16). The vowel *ā* sustains the same change in each, notwithstanding this difference in speed, because the *e* into which it changes is more persistent than the other vowels in the series, as will be more fully explained a little later. It will also be instructive to compare (16) with (17). The *ā* in the former rises to *e* on passing from one to three revolutions, while in the latter it rises only to *a♯*, which sound would have passed into *e* on a slight increase of speed. In (16) the speed was doubtless a trifle higher than in (17) as well as in (15).

It must also be remembered that at certain stages a sound will be on the point of passing from one recognized vowel into another, so that it may be difficult to denote its sound exactly by any of the conventional signs usually employed. For this reason it might be preferable to substitute the symbols used by Mr. Melville Bell in his "Visible Speech."

Furthermore, we have noticed in some cases that a very trifling difference in the quality of the vowel impressed upon the cylinder at a low speed may cause a decided change in the vowel sound given out at a considerably higher speed. Thus, the vowel *e* reproduced at increased speeds passes into a high *ị̄* and then into *i*. But if a series of *e*'s be spoken into the instrument, it is possible to find a speed of reproduction such that some of them are heard as *ị̄*'s and some as *i*'s. On raising the speed the *ị̄*'s tend to rise to *i*, and on lowering it the *i*'s tend to fall to *ị̄*.

Some interesting peculiarities of different vowels were observed in the course of our experiments.

It was noticed that, in several cases where the vowel seemed to have quite lost its peculiar quality, there was nevertheless a certain reminiscence, so to speak, of its original character remaining. This appeared to be due to the logographic differences among the various vowels. Of course, the logographic characteristics of any vowel are not altered by the speed at which the sound is reproduced, so that in many cases we necessarily reproduce a sound with a characteristic resonance note belonging to one vowel and a logographic character belonging to another. Where the logographic character is clearly marked, this may enable one to recognize the vowel sound originally spoken into the phonograph, even though the characteristic resonance note is quite changed. This is especially true when the vowel forms part of a word.

There also appears to be a great difference among different vowels in what we may call the persistence of their vowel character when the speed of reproduction is varied. Whereas some, as ŏ, ō, and ä, change their character completely on increasing the speed, say to double its original rate, others change far less. The vowel ē seems particularly persistent under a large change in speed. With it as with all vowels there is necessarily a shortening at higher speeds, as denoted in the tables by a dot placed under the letter; but apart from this the speed may be varied more than for any other vowel studied by us before any marked change in its quality appears.

In order to form some estimate of the extent to which the context would influence the judgment as to the character of a vowel sound, the experiment was tried of reproducing at different speeds a sentence or verse spoken into the instrument. Thus the words from a negro melody containing the vowel ō many times repeated were spoken, as follows: —

"Roll, Jordan, roll !
Roll, Jordan, roll !
I want to go to heaven when I die
To hear old Jordan roll."

These words were impressed upon the cylinder at a speed of three revolutions per second, and were reproduced at speeds of two revolutions and one revolution per second respectively, with the following results. At two revolutions the ō's were in all cases plainly recognizable though lengthened; but at one revolution the quality was completely altered, ō having become changed to ŏ in all cases. Like results were observed in other sentences containing the vowel ō.

In like manner the sentence "This was the noblest Roman of them all" was impressed upon the cylinder at a speed of one revolution. Reproduced at two revolutions, the ō's had a sound which closely approached *u*. Lowering the speed slightly changed it to a very short ǫ ; and raising the speed slightly, to a clear *u*. At three revolutions the quality of all the vowels was so completely changed that the sentence was entirely unintelligible even to one knowing what it really was, the rapidity of the speech, as reproduced, however, contributing largely to this lack of intelligibility. To avoid this latter source of difficulty, the same sentence was spoken into the instrument at a speed of two revolutions, and reproduced at one revolution and also at three revolutions. At the lower speed the *i* in "this" changed to *a*, so that, the *s* in "this" being rather indistinct, the word seemed almost to have changed to "that." But the ō's, while deepened in quality, did not apparently actually change to ö. Lowering the speed still more caused a closer approach to this, but the ō quality still seemed to persist. This was doubtless due in part to the association of the sound with the word, and in part to the acoustic effects due to logographic pressure, and to the connection of the vowel with the preceding consonants. To study these, the same sentence, preceded by four ō's and followed by the same number, was spoken at two revolutions and reproduced at one revolution. The separate ō's seemed to fall to ö, and there was likewise a perceptible fall in the same sounds in the body of the sentence, but these seemed still to retain their ō sound. To test the matter still further, the same sentence with the ō's mispronounced was spoken into the phonograph, at a speed of one revolution, as follows: "This was the nöblest Röman of them all." On reproducing it at two revolutions the ö's changed to ō, and the sentence was clearly heard with the mispronounced words rectified, and as distinct as if they had been properly pronounced when impressed upon the cylinder, and reproduced with the same speed of the cylinder as when uttered. Lowering the speed below one revolution, the ö sounds became still deeper and clearer.

As the vowels ō and ö are more persistent in their character than some others, a similar experiment to those already described was tried with the line, "Though the harbor bar be moaning." This was impressed upon the cylinder at a speed of one revolution per second. Reproduced at two revolutions, the words "härbor bär" became "harbor bar" (*a* as in *hat*), and at three revolutions the ä's in the same words assumed a nasal quality somewhat approaching the French nasal *in*.

The further experiment was performed of sounding the five vowels *ā ē ī ō ū* successively into the cylinder when this made one revolution per second, and reproducing them at three revolutions. It was found that the quality of the different vowels was altered so that they were unrecognizable by one ignorant of the sounds which had actually been spoken by the voice. The same result was reached with the vowels *ä e ē ọ̄ ö*, and also with *ö ō ä e i*. The last mentioned series, which is No. 20 in the tables, was impressed upon the cylinder at a speed of one revolution, and reproduced at two and at three revolutions, approximately. At two revolutions the series seemed to have changed to *ō ou a♯ ẹ ị*, the *a♯* closely approaching the French nasal *in*. At three revolutions the sounds heard were *ọ̄ ou♯ a♯ ị̄ u♯*, the *a♯* being a clear nasal *in* and the *u♯* a very short *u* with a high resonance note.

The limitations in speed of the phonograph cylinder, as the instrument is constructed for practical purposes, have thus far prevented us from carrying the range of changes in the pitch of the reproduced sounds as far as is desirable. This defect we purpose to remedy by suitable modifications in the driving gear of the apparatus. For reasons already explained, it is also desirable to measure the relative rates of rotation more accurately than we have been able to do with the commercial form of the phonograph.

We hope that we may be able to continue this investigation by a more systematic study of the behavior of the reproduced vowel sounds, and likewise to consider the effect of changed pitch in reproduction upon the various consonantal sounds.

In connection with the present subject, it is interesting to consider the unconscious testimony to the existence of different characteristic resonance notes for the different vowels which is given by various onomatopoetic words. The words used to denote various sounds form an excellent example, as will appear from the following list of a few such words in which the pitch of the sound denoted is higher as the list proceeds: — boom, gurgle, roll, toll, roar, slump, thump, crash, smash, crack, snap, bang, jingle, ring, hiss. It will be observed that the vowels in the later words are those with higher resonance notes.

Rogers Laboratory of Physics,
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