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Physics. — "*The effect of the induction coil in telephonic apparatus*" (2nd part). By J. W. GILTAY. (Communicated by Prof. P. ZEEMAN.)

(Communicated in the meeting of December 28, 1901)

To arrive at our purpose we shall now try another method. Let us suppose an induction-coil without iron; in the primary wire is an undulatory current, in the secondary wire an alternating current is induced. If we now slide an iron core into that coil, the coefficient of mutual induction will get $\frac{A}{B}$ times greater, *and if we take care that the strength of the current in the primary wire rests at the same value, notwithstanding the introduction of the iron*, the induced current will also be $\frac{A}{B}$ times stronger than it was before. We shall now investigate whether this $\frac{A}{B}$ has the same value for all our coils.

As, however, it would be difficult to make the intensity of the primary current after the introduction of the iron core equal to what it was before, we shall try to reach our aim in an indirect way.

Fig. 9 shows how we set about for this experiment. To find the value of $\frac{A}{B}$ for a coil with 3 primary layers, the primaries of 3 A and 3 B were connected with microphone and battery in one circuit. *a* is a small coil with wire and an iron core in it, quite similar to that of the electro-dynamometer. Now the secondary of 3 A was connected with the coil *a* and the secondary of 3 B with the electro-dynamometer. So now we measured the current induced by 3 B. By means of a commutator, left out of Fig. 9 for clearness' sake, the electro-dynamometer was made to change places with coil *a*, so that 3 A was connected with the measuring instrument and 3 B with coil *a*. So now the current induced by 3 A was measured, and the strength of the current in the primary circuit had necessarily remained unaltered in both cases.

Fig. 10 shows more elaborately how this experiment was arranged. If the 4 Morse keys are pressed down, 3 A is connected with the electro-dynamometer and 3 B with coil *a*. If the keys are in rest, 3 A is connected with coil *a* and 3 B with the measuring instrument.

The result of these measurements are given in Table IV. For every measurement or comparison of 2 coils with each other 33 turning points were read as formerly. As is seen from this table

$\frac{A}{B}$ has a smaller value for the coils of higher order than for those of lower order.

TABLE IV.

Coils:	i Mean deviation in minutes.	k Mean deviation in minutes.	$\sqrt{\frac{i}{k}}$
3A 3B	526.5	12.4	6.52
6A 6B	337 5	9.7	5.9
9A 9B	410 3	13 5	5.51
12A 12B	186 1	8.15	4.78
15A 15B	501 1	32.3	3.94

The explanation of this phenomenon we shall have to look for in the fact that for the coils of higher order the secondary turns are farther removed from the iron core than for those of lower order. On account of this, for the former coils many of the lines of force, originating from the iron and being closed curves, will cut the cylindric space in the secondary coil twice, in 2 opposite directions. So these curves of force are entirely without value for producing induced currents in the secondary.

If the induction coils were arranged in such a way that the iron core formed a ring closed in itself, the above mentioned phenomenon could not take place, as then each line of force would cut the space in the secondary coil only in *one* direction.

If we write down the values for $\frac{A}{B}$, found according to the two different methods represented respectively in Fig. 3 and Fig. 9:

Coil	3	6	9	12	15
$\frac{A}{B}$ found according to fig. 9	6.52	5.9	5.51	4 78	3.94
$\frac{A}{B}$ found according to fig. 3	5.56	3 95	2 59	1.95	1.48
Weakening of the primary current by the iron	1.17	1.49	2.13	2.45	2.66

we see that the figures of the 2nd row and those of the 3rd row differ pretty much.

In measuring according to Fig. 9 we have taken care that the primary strength of the current always had the same value, whether the induced current of coil A or that of coil B was measured. When measuring according to fig. 3 we have *not* heeded that. So if the two methods give different numbers, the reason can be looked for only in the change which the strength of the primary current suffers in consequence of the iron.

Comparing the numbers of the 2nd with those of the 3rd horizontal row of the table given above, we see that the latter are all smaller than those of the 2nd row. This must evidently be explained from the fact, that in measuring according to fig. 9, only the useful factor of the influence of the iron — the increasing of the coefficient of mutual induction — is prominent, whilst if we act according to fig. 3, the disadvantageous factor of the influence of the iron also has a part in it: the increasing of the self-induction of the primary and the weakening of the primary current caused by it.

Besides the fact that the numbers in the 3rd row of the above table are smaller than those in the 2nd row, we also see that the 3rd row converges much more. This is due to the weakening of the primary current by the introduction of the iron core being greater for the coils of higher order than for those of lower order. So the disadvantageous factor of the iron is the greatest for coils of higher order. This weakening can be calculated by dividing the numbers of the 2nd row by those of the 3rd; the numbers obtained in this way I placed in the 4th horizontal row of the table.

Although it is sufficiently known that this weakening of the current by the iron increases with the number of primary turns, yet I have tried to show it experimentally by the measurements of which table V gives the results.

TABLE V

Coils	i. Mean deviation in minutes.	k. Mean deviation in minutes.	$\sqrt{\frac{i}{k}}$
3A	470		1.036
3B		504.5	
15A	111		1.539
15B		263	

The method followed for getting these results is shown in Fig. 11. T is the translator without iron, already mentioned on page 369. G is the electro-dynamometer, which for this experiment however is provided with thicker wire. The thickness of this wire is 0,2 mm., the resistance 42 Ohm. *a* is the coil with the iron core in it, which we used before. Before the microphone are the resonator and the tuning fork as before. If the 4 keys are pressed down, the primary of 3 A is connected with the electro-dynamometer and the translator; and the secondary of 3 A is connected with coil *a*. If the keys are on the contact of rest, 3 B has changed places with 3 A. These comparative experiments were made with the coils 3 and the coils 15; it is true, that table V shows but a very trifling influence of the iron, but yet it is clear that the influence is greater for 15 than for 3. These numbers cannot have an absolute value, the introduction of the translator and of the electro-dynamometer in the primary circuit greatly increasing the self-induction. On purpose to make this increase as small as possible, we provided the electro-dynamometer with thicker wire. If this experiment could be made with a measuring-instrument and a translator without self-induction we would of course have got 1,17 for coil 3 and at 2,66 for coil 15 (see row 4, table page 402). The proportion of those numbers, $\frac{2,66}{1,17} = 2,3$, should correspond with the proportion of the final numbers of table V. This gives however for that proportion only 1,5.

The cause of this far from favourable result was due to the fact, as I afterwards found, that the microphone was not in good order when I made these measurements (they were the last I made with it). When it was connected with a telephone and a battery the former made a creaking sound, whilst no sound at all was made in the vicinity of the microphone.

Now we know that the phenomenon, that the iron in our coils of higher order has smaller efficiency, than in those of lower order, is due to 2 facts:

1. to the fact, that for the coils of higher order the secondary wire is wound on a wider cylinder, which causes many of the lines of force to cut twice the hollow space of that cylinder.

2. to the weakening of the primary current when the iron is introduced, by the increase of the self-induction, which weakening is greater for the coils of higher order than for those of lower order.

As is seen from the numbers of the 2nd and 3rd rows on page 402, the cause mentioned sub 2 is the most important. This is also clear if we note that the primary coil is the only object with self-induction in the primary circuit, as the self-induction of the microphone, the microphone-battery and the very short connecting wires are practically equal to 0.

So we have determined the influence of the iron on the intensity of the induced current in two ways: 1. by letting the harmful as well as the favourable influence of the iron act freely and 2. by bringing out only the favourable influence.

I have determined the influence of the iron still in a third way, standing midway between the two above-mentioned methods. This method is represented in fig. 12 and fig. 13; the arrangement of the experiment is shown a little more in details in fig. 14. As fig. 12 shows, the two primary wires of coils A and B, which are to be compared, are connected in one circuit with the microphone and the microphone battery. The secondary of A is connected with the electro-dynamometer, the secondary of B remains open. The electro-dynamometer is now again the same as the one used for all the other experiments except for those of table V. In this way the current induced by A is measured. Now the secondary of coil B is connected with the electro-dynamometer, the secondary of A remaining open, as fig. 13 indicates. This change was made by means of the 2 Morse keys, as is shown in fig. 14: when the keys were pressed down, 3 B was connected with the measuring-instrument; if the keys were in rest, 3 A was connected with it.

The values for $\frac{A}{B}$ found according to this method are placed in the 3rd horizontal row of the following table. The measurements were taken in quite the same way as indicated in tables II and III.

Coil	3	6	9	12	15
$\frac{A}{B}$ found according to fig. 9	6 52	5.9	5 51	4.78	3.94
$\frac{A}{B}$ found according to fig 12, 13 and 14	4.94	5 03	4.91	4 25	3 92

As will be seen, $\frac{A}{B}$ is smaller in the 3rd row than in the 2nd row, for all coils. This is made clear by the following consideration:

In fig. 13 the current of B is measured whilst the secondary wire of A is open. On the other hand, in fig. 9 the secondary of A was closed when the current of B was measured. This closing of the secondary wire of A weakens the variations of the magnetism of the iron core, and by this weakening the current in the primary is strengthened; so the deviation given by coil B to the electro-dynamometer will be greater in the case of fig. 9 than in that of fig. 13.

In fig. 12 the current of A is measured whilst the secondary wire of B is open. In fig. 9 the secondary of B was closed whilst A was being measured. The opening or closing of the secondary of B will however give rise to only a trifling difference in the strength of the primary current, and the deviations given by A to the electro-dynamometer will have about the same value whether the measurements are made according to fig. 12 or to fig. 9.

The result is that $\frac{A}{B}$, determined according to fig. 9, must be greater than $\frac{A}{B}$ measured according to fig. 14.

We see that the difference between the numbers of the 2nd row and those of the 3rd row is smaller for the coils of higher order; for coil 3 the difference is rather great, whereas for coil 15 it has almost disappeared. This is owing to the fact, that the closing of the secondary in a coil of higher order causes a *smaller* decrease in the magnetic changes of the iron core than in coils of lower order.

The reason for this is 1. that the current induced in the secondary is weaker for 15 A (for instance) than for 3 A, and 2°. that the secondary turns are farther removed from the iron in 15 A than in 3 A. This is also proved by the following experiment: I took the coils 3 A and 15 A of fig. 7 (changed into telephones) and again arranged the experiment as in fig. 8. The tuning-fork was placed near the resonator, the microphone-battery consisted of a storage-cell. Both telephones, the secondaries being open, gave a strong sound. If the secondary of 3 A was closed, the sound produced by this telephone, became perceptibly weaker; if the secondary of 15 A was closed, there was no difference perceptible in the intensity (though there was in the quality). The same experiment was repeated after the storage-cell had been exchanged for a Leclanché-cell, i.e. with a weaker undulating current. With coil 3 the closing of the secondary produced a very perceptible weakening of the sound; with 15 now a slight weakening of the sound was noticed when the secondary wire was closed but it was extremely small. [1])

When we divide the numbers, found on page 367 for the effect of the various A coils, by the values of $\frac{A}{B}$, found on page 402, we obtain for the effect of the various B coils:

Coil:	3	6	9	12	15
Strength of the induced current of the A coils:	1	1.507	1 429	1 114	0.818
$\frac{A}{B}$:	5.56	3 95	2.95	1.95	1.48
Strength of the induced current of the B coils;	0.18	0.38	0 48	0.57	0.55

[1]) At first it was my intention in writing this paper not to mention the experiment of fig. 14, the question concerning the influence of the iron being to my idea sufficiently answered. But on the other hand it seemed to me that these numbers could serve to heighten the trustworthiness of the other results arrived at by me, as the reason of the differences between the numbers of the two rows on page 405 was, to my idea, perfectly explained. And where quantitative investigations are made with such capricious apparatus as microphones and electro-magnetic tuningforks, an indirect confirmation seemed not superfluous.

From this we see, that the decrease of the intensity of the induced current by the increase of the number of primary turns is much smaller for the B coils than for the A coils. The intensity increases as we see, from 3 B to 12 B, but that increase becomes less and less and is at last negative from 12 B to 15 B. The reason for 15 B giving a weaker induced current than 12 B can be found in the increase of resistance of the primary circuit, without reckoning with the self-induction:

The resistance of the microphone is 3.5 Ohm, that of the coil 12 B is 4.9 Ohm and that of 15 B 6.4 Ohm; the resistance of the microphone can be neglected. Then in the first case the whole resistance of the primary circuit is 8.4 and in the second case 9.9 Ohm. The proportion of those resistances is 1.18; the proportion of the number of turns in both cases is $\frac{15}{12} = 1{,}25$.

If we introduce into a circuit, in which a microphone and a battery have been placed, a dead resistance causing the entire resistance (when the microphone is at rest) to become n times greater, the strength of the current will be reduced to $\frac{1}{n}$ of its former value and the change of resistance in the microphone will also retain but $\frac{1}{n}$ of its former value. The undulations of the primary current will be reduced in this case to $\frac{1}{n^2}$ of their former value.

So in the above-mentioned case, by substituting coil 15 for coil 12, the undulations of the primary current become $1{,}18^2 = 1{,}39$ times smaller. On the other hand the number of primary turns becomes 1,25 times greater. So according to this calculation, the induced current given by 12 B would have to be $\frac{1{,}39}{1{,}25} = 1{,}11$ times stronger than those given by 15 B. The numbers in the table on page 406 give for that proportion $\frac{57}{55} = 1{,}04$. If we take into consideration that the measurement of the resistance of a microphone at rest often gives very different values, then we may consider the correspondence between these two proportions to be quite sufficient.

In the table on page 406 we see, that when 6 A connected with microphone and battery gives an induced current 1,507, 15 B will induce in the same circumstances a current 0,55. That proportion

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$\frac{1,507}{0,55} = 2,73$ shows us, that with coil 15 B in our microphone-circuit, (i. e. with a coil without iron), we shall hear as much as with 6 A (the best of our coils, as far as intensity goes) if only we use 2,73, let us say 3 times, the number of cells as for 6 A. The resistance of the battery is neglected and moreover this calculation holds good only for the tone Fa 3.

The experiment with the telephone confirmed this entirely. Before the microphone the tuning-fork and resonator were placed as usual; by means of 4 Morse-keys we could bring into the circuit 6 A with 1 Leclanché-cell as well as 15 B with 3 cells It was found that not the slightest difference in the intensity of the sound was to be heard whether 6 A or 15 B was used. In the same way I compared 15 A with 2 Leclanché-cells with 15 B with 3 such cells. In both cases the intensity was exactly the same.

Sharper tones are weakened in a greater degree by the self-induction of the primary coil than lower ones. If I had made these experiments with a tuning-fork of a sharper note, I would have obtained other numbers; the series I found on page 367 for $\frac{A}{B}$ would have converged much more.

We have till now occupied ourselves only with the *intensity* of the currents (or of the telephonic sound) induced by our various coils. We shall now try to investigate which coils are best adapted for a pure articulation.

In general we can assume that for our purpose those coils in the first place come under consideration, which render a simple tone, produced before the microphone, also as a simple sound in the telephone; and which will reproduce a compound tone in such a way that the mutual relation of the intensities of the simple tones out of which the compound consists, is the same for the reproduced sound as it was for the original sound. Theoretically the induction coils with iron core must necessarily be inferior to those without iron:

1. because by the self-induction of the primary coil with iron the sharper tones weaken more than the lower ones, so the quality of the reproduced sound will not be the same as that of the original. This is in less degree the case in the coils without iron.

2. because a simple sound does not induce one sinusoidical current in the secondary wire of a coil with iron core, but two such currents, which are somewhat shifted in respect to each other. One of the sine currents is induced by the primary current, the other

by the magnetism of the core. For the sake of brevity we shall call the former the galvanic, the latter the electro-magnetic induction current. Now as the strengthening and weakening of the magnetism of the iron core, caused by the changes of the primary current, requires a certain time, the induced currents, produced by those changes of magnetism will appear and disappear later than the currents induced directly by the primary current. The tables given on pages 402 and 406 enable us to calculate about how many times the electro-magnetic induction current is stronger for the different coils than the galvanic. So e.g. for coil 3 A:

The currents induced by 3 A and 3 B are in the proportion 1 : 0.18 (table page 406). The primary current of coil 3 B becomes 1.17 times weaker by the introduction of the iron (table page 402). So the galvanic induction current produced by coil 3 when iron is introduced into it (in other words the galvanic induced current given by coil 3 A) has the intensity $\frac{0.18}{0.17} = 0.15$ if 1 is the whole current induced by 3 A. Now the latter current is the sum of the galvanic and of the electro-magnetic current; the galvanic being $= 0.15$, the electro-magnetic will be equal to 0.85. It follows from this, that the electro-magnetic induced current for coil 3 A is $\frac{85}{15} = 5.7$ times stronger than the galvanic.

In this manner we find for the coils 3 A, 6 A, 9 A, 12 A, 15 A
the proportions 5.7, 4.9, 5.25, 3.8, 3.0.

With 3 A the electro-magnetic induced current will be so much stronger than the galvanic, that the latter will not be able to give any change to the quality of a simple sound. If we suppose the amplitude of the diaphragm of the telephone to be proportional to the strength of the induced currents, the intensity of the sound will be proportional to the square of the strength of the current. For 3 A the electro-magnetic tone will be $5.7^2 = 32$ times stronger than the galvanic: so it is not probable that the latter will have any perceptible effect.

In this respect 3 A will probably be the best coil as far as articulation goes. But also in respect to the 2nd condition, named on page 9 for a good articulation, 3 A will be the best of our A-coils, the self-induction being less than in any of the 4 other A-coils.

With 15 A the proportion of the electro-magnetic induced current to the galvanic $= 3$, so the proportion of the two tones $= 9$. In using this coil there will be the greatest chance that a simple tone made before the microphone will be reproduced with changed timbre by the telephone. And with 15 A the self-induction is also greater than with the other four A-coils, so in this respect also 15 A will be the least suitable for pure articulation.

With 15 B of course the double curves do not appear at all and the self-induction is much less than with 15 A. So we can expect 15 B to articulate better than 15 A.

In order to investigate in how far difference of articulation was perceptible with the different coils, I compared 3 A with 15 B, likewise 6 A with 15 B and finally also 15 A with 15 B. Of course the battery was chosen in such a way that the intensity of the sound remained the same with the two coils under comparison. So for instance in using 15 B (see table on pag. 406) 3 times more elements had to be taken than for 6 A. It was however evident, that the microphone got too much current with 3 Leclanché-cells and 15 B, as, even though no sound was made in its vicinity, it began to vibrate and to make a noise in the telephone. I therefore made use for these experiments of a thermo-electric battery of GÜLCHER consisting in all of 66 couples. In comparing 6 A with 15 B I made the former coil act with 7 couples, the other with 21 couples; in comparing 15 A with 15 B I used respectively 15 and 21 couples, etc. Now an article of a newspaper was read before the microphone and by pressing down or releasing 4 Morse-keys the 2 coils under comparison were exchanged. It appeared *that not the slightest difference in articulation was perceptible*, either when comparing 3 A with 15 B, 6 A with 15 B, or 15 A with 15 B. Women's voices generally sounding clearer out of our small telephones (with small, thin diaphragms) than men's voices, the experiments were also made with these, but with the same negative result. The telephone spoke equally clear in all the different cases.

To investigate whether in a musical sound change of quality would be perceptible when the coils were exchanged, the experiment was made with a musical box and also with the tuning-fork Fa 3, but without any result. To avoid the influence of the proper tones of the telephone-diaphragm, the telephone was substituted by a condensor with a permanent charge of about 32 volts, but the result was the same.

As in many cases, also here practice has found the right way. The induction coils with iron and 4 or 6 primary layers of wire in

Fig. 9.

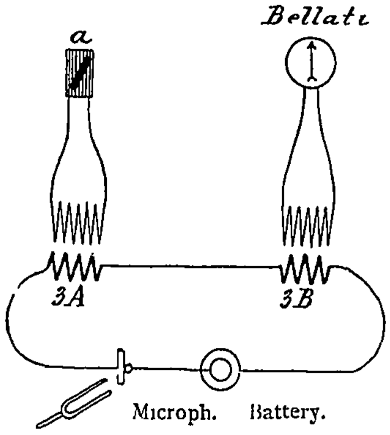


Fig. 10.

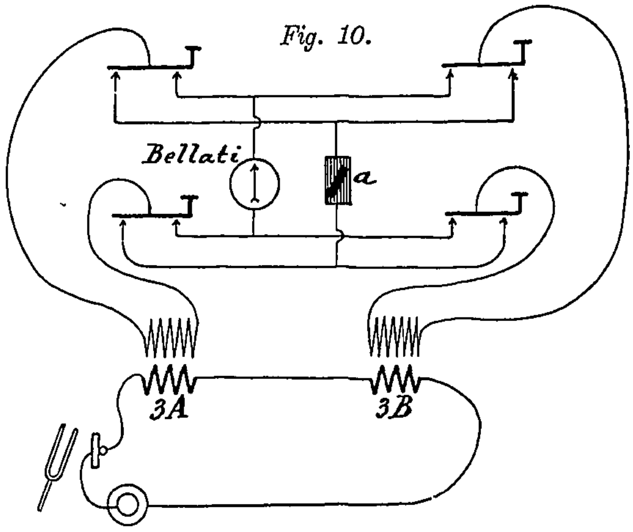


Fig. 11.

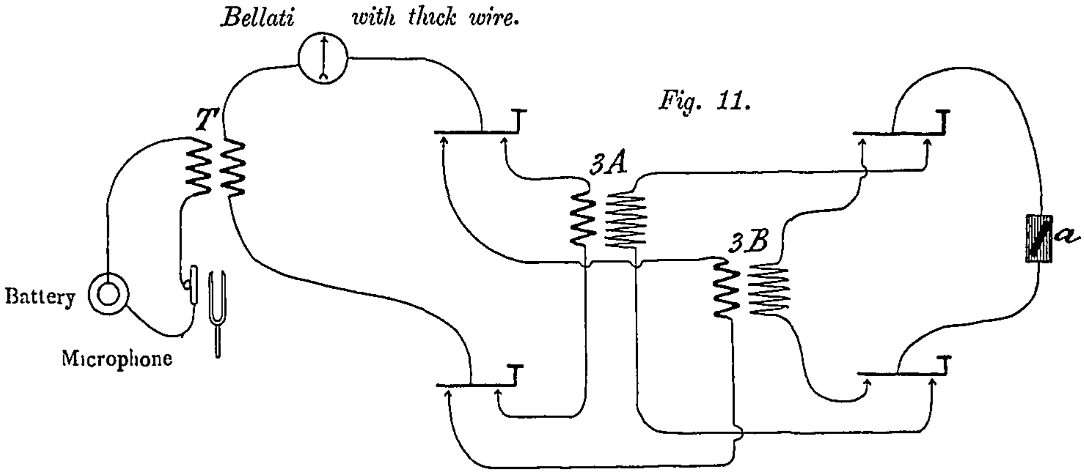


Fig. 12.

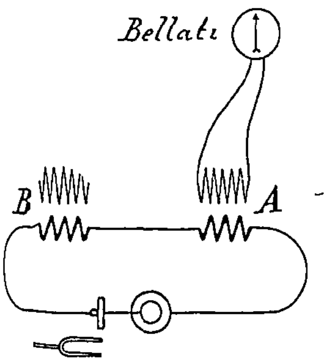


Fig. 13.

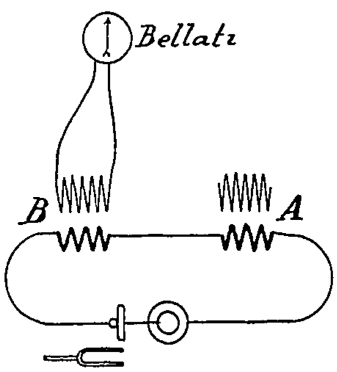
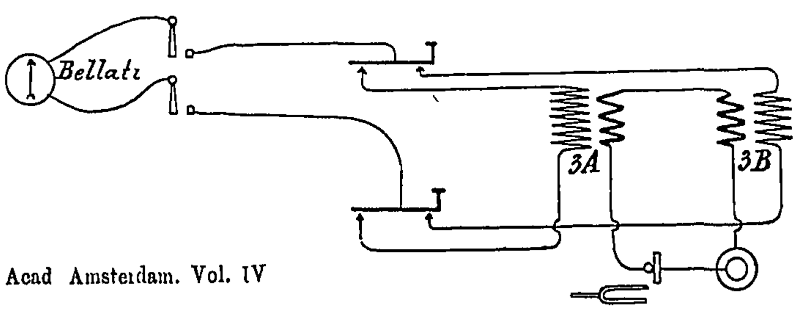


Fig. 14.



general use in practice, give the strongest sound and although theoretically they ought to articulate less accurately than coils with more primary wire and no iron, in practice this is not at all perceptible, not even in laboratory-practice, which is the only practice I have a right to speak of. Our sense of hearing is evidently so accustomed to content itself with defective sounds and to understand them that we cannot at all observe the small differences in the accuracy of the reproduction, which must undoubtedly exist when using the different coils.

I cannot omit quoting some lines of HEAVISIDE, [1]) who expresses himself as follows, after having enumerated the different distortions to which telephonic transmission is exposed before the sound of the telephone is observed by us:

"And yet, after all these transformations and distortions, practical telephony is possible. The real explanation is, I think, to be found in the human mind, which has been continuously trained during a lifetime (assisted by inherited capacity) to interpret the indistinct indications impressed upon the human ear; of which some remarkable examples may be found among partially deaf persons, who seem to hear very well when all they have to go by (which practice makes sufficient) is as like articulate speech as a man's shadow is like the man."

As respects practice it is evident that nothing is to be learnt from my paper. The only thing deducible from it, is perhaps the following: On very long telephonic cables where all slight influences which might weaken the transmission of the sound, must be avoided, it is the custom that each station shunts the secondary of its induction-coil during the time that it takes a message, by pressing down a button. The telephonic currents coming from the sending station need not in this way pass through the secondary of the receiving station and are not needlessly weakened by the self-induction of that secondary with iron core. If now we were to take a coil with more primary layers and no iron, the self induction of the secondary would be much smaller and the troublesome shunting during the listening might perhaps be avoided. But no doubt the shunting of the coil is the more efficacious means to prevent the weakening of the telephonic currents.

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[1]) OLIVER HEAVISIDE, Electrical Papers, Vol II, Page 348.