THE TONOSCOPE

BY

CARL E. SEASHORE

In experimental psychology instruments have as a rule been designed to meet immediate needs, and have usually been described incidentally in reporting the results of psychological investigations. Much research has been wasted because done with untried apparatus. In fact most of our instruments are in a crude condition; and many fields of investigation lie untouched for want of measuring instruments. It is a sign of a higher stage in the science that the most essential psychological instruments are now being subjected to investigation apart from the specific pending psychological use. Only in this way can we properly develop instruments and standardize the technique of manipulation. I therefore take pleasure in presenting the description of an instrument and its use, as an object worth while in itself.

The tonoscope, Fig. 1, works on the principle of stroboscopic vision, the principle of moving pictures. Auditory vibrations of air, caused by voice or musical instrument, are converted directly and instantaneously into visual configurations on a screen, and the vibration frequency which denotes the pitch of the tone may be seen in plain figures on a scale. This enables us to measure the pitch of any tone by direct inspection while singing, speaking, or playing under normal conditions. The ability to do this opens up countless problems in the psychology of tonal expression.

There is a contrivance by which the vibration of the voice mechanically raises and lowers a flame for each sound wave. The oscillation of the flame results in corresponding exposures on the screen which it illuminates. The vibration being rapid, the retinal lag produces the effect of continuous vision, although the duration of the illumination for each vibration is very short in comparison with the corresponding period of non-illumination. In moving pictures it is well known that, if we have successive pictures which are alike thrown on the screen in the same place and in rapid succession they form one continuous picture which stands out clear and still. This is the principle here employed. The revolving screen,

rotating at the rate of one revolution per second, carries rows of dots, regularly spaced but varying in number for each row. When a tone is sounded, the row which has the dot-frequency that corresponds to the vibration-frequency of the tone will stand still and be clear while all other dots move and tend to blur. Each row runs under a number on the scale. The row which stands still, therefore, points to a number which designates the pitch of the tone. The screen contains a sufficient number of rows of dots, varying in number, to correspond directly, or by multiple, to all tones within the range of the voice. To see the pitch of the tone one has therefore only to see the number of the line that stands still.

Earlier models of the tonoscope have been described in a previous volume of these Studies (1); also in the Musician (2). Such radical changes have, however, been made since then that we are now dealing with an instrument very much modified and extended in its usefulness.[1] The present instrument is not the result of the work of one man but of many of whom, aside from those who have developed the principle of stroboscopic vision in physics, I desire to mention particularly Dr. E. W. Scripture who designed the first laboratory exercise using this principle in psychology (3); Dr. C. F. Lorenz (4), to whose ingenuity and most generous coöperation we owe the synchronous motor and the plan of using the selenium cell with the siren; Mr. E. W. Bechly, and Professor E. A. Jenner, who made the first tests with the tonoscope in determining its value for use in the musical conservatory (5); and Dr. Walter R. Miles (6), who has standardized procedure for various problems in the measurement of singers with this instrument.

Instead of giving merely a description of the commercial form of the instrument, I shall attempt to suggest, in a semi-technical way, its various possible forms on the basis of actual experiment from the laboratory point of view. The essential features which must be discussed in turn in the description are the speed regulation, the screen, the dot grouping, the sensitive light and sound transmitter, and the siren.

The synchronous motor.—The validity of stroboscopic frequency measurements depends upon the accuracy with which the movement

[1] Fig. 2, showing the 1902 model, is here reproduced because it shows the bare elements of construction better than they can be seen in the present encased model, as shown in Fig. 1.

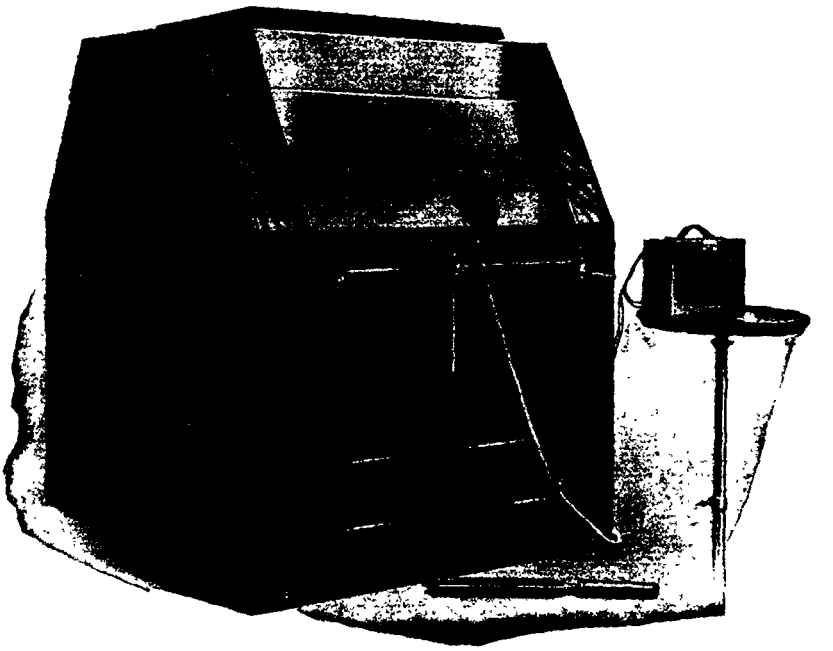


FIG. 1. THE TONOSCOPE

(The instrument seen at the right is the acousticon.)

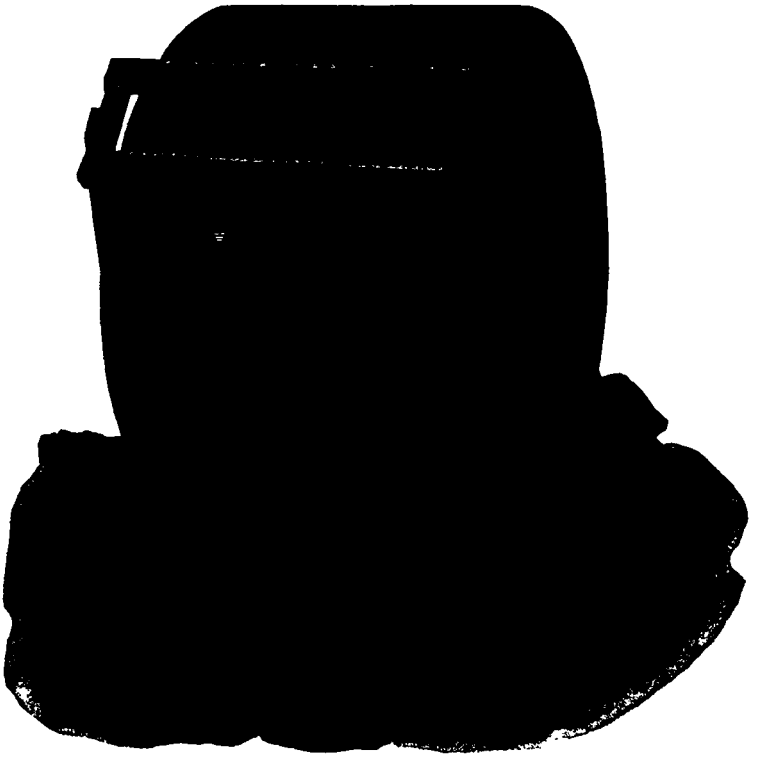


FIG. 2. EARLY MODEL OF TONOSCOPE. (1902)

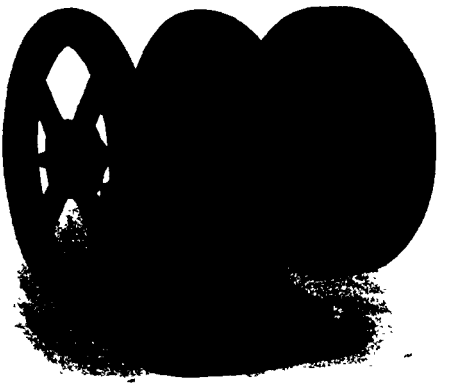


FIG. 3. THE SYNCHRONOUS MOTOR

of the exposed object is controlled. The method employed in the early models proved entirely too laborious and inconvenient.[2] The final solution was found in the use of a synchronous motor which drives the drum (screen) at a regulated speed. This motor (Fig. 3) works on the principle that, if a regularly interrupted current be sent through a multipolar field, and the needed initial momentum be given to the revolving multipolar armature, each closing of the circuit will synchronize with poles always in a corresponding position of approach, and the momentary pull will be sufficient to continue the rotation until the next pull occurs, at the next approach of poles. This is the principle of La Cour's "phonic wheel" (7), a principle also employed by Lord Rayleigh (8).

A motor of this type is mounted on the main shaft of the tonoscope drum.[3] The drum, serving as a balance wheel and being connected to the motor by a coil spring, furnishes the right degree of inertia and flexibility in the transfer of the pull.[4]

A large 10 v.d. tuning fork is used as an interrupter. It is energized by primary cells, and is encased in a box which is kept out of the way in a closet so that no noise shall come from it. A 16 c.p. lamp used for resistance in the motor circuit, is mounted

[2] In the early models the drum was driven by an ordinary direct current motor. An assistant at the back side of the drum observed and recorded the actual speed at the time of every reading. This was done by means of the stroboscopic effect of the intermittent light in a vacuum tube in circuit with a standard tuning fork. Every reading had to be adjusted with reference to an elaborate table of corrections calculated for different steps of variation from the true speed.

[3] In the early stages the motor was placed outside of the drum and the power was transferred by belt. This was neither as convenient nor as reliable as the present method, but it left the motor available for other laboratory purposes.

There is a great demand for such a synchronous motor in laboratories because, with constant speed and power, many of the laboratory problems are readily solved and we gain a higher degree of accuracy than can be obtained by any other form of electric motor or by kymograph clockworks. As the speed may be transformed up or down, this motor will take the place of many cruder devices in the physics and psychology laboratories for securing constant motion, marking intervals, measuring time, making exposures, etc.

[4] In the type of motor here needed this principle has not before been successfully developed for practical use. The hitch lies in the jerky nature of the pull. By attaching a flywheel to the axle by a flexible connector we get a flexible moment of inertia which solves the problem.

between the prongs of the fork and proves a convenient means of keeping it at a sufficiently constant temperature, the temperature being that to which the fork is raised by the heat of the lamp within the box.[5]

A 110 volt direct current is completed through the motor and a mercury contact interrupted by the fork. The current is reduced by the lamp resistance. The make-and-break is short-circuited with a condenser to avoid forming of an arc. A large amplitude of the fork, fully 10 mm., also helps in preventing the tendency to arc.

A rheostat inside the tonoscope case, with a switch on the surface, serves for the adjustment of current, as there may be fluctuations in the supply main. A small detachable crank for starting fits the end of the main shaft which comes out flush with the edge of the case on the side. To start the tonoscope one has only to start the fork, give the drum a turn up to approximately one revolution per second and close the switch. Once started, the instrument will run indefinitely and there is no care or distraction in the running of it.

The screen.—The stroboscopic screen is formed by mounting a sheet of aluminum in the shape of a drum over a heavy balance wheel. A section of this drum is seen through the opening on the front of the case (Fig. 1). This screen is 50 cm. wide and has a circumference of 242 cm. The balance wheel is heavily mounted on ball-bearings resting on a heavy iron frame. The whole instrument is enclosed in an oak case with doors on every facet.

The size of the drum is determined by the minimum area for the legible distribution of 18,500 markings, or stroboscopic dots. In the present screen the dots are bored holes, three and one-half mm. in diameter. The inside of the drum being dark, the holes show up clearly as black spots on the light aluminum surface. These holes are spaced with the highest mechanical accuracy and are arranged in 110 parallel rows, each completing the circumference of the drum in uniform spacings for each row (Cf. arrangement of dots in screen in Fig. 2). One row has 110 dots and the dot frequency in the remaining rows increases by one dot for each row up to and including 219. Thus we get frequencies to correspond

[5] Like the motor, this fork becomes a sort of "universal" apparatus in the laboratory. Being standardized and always connected up, it becomes the most convenient means for timing purposes. It is notably serviceable in connection with a multiple recorder which makes impressions on ticker tape.

to each intergral vibration-frequency in an octave of tones, the octave of 110 v.d. to 220 v.d. This is approximately the octave from *A* up to the *a* below middle é

This octave was chosen after much experimenting as being the most serviceable, all factors taken into consideration. Within this octave the tones are read directly, and above and below it they are read by multiples. The number of holes in each row is shown in plain large figures on the scale. When the drum revolves the row formation stands out clearly and each row points to a number.

The "framing-effect".—As may be seen in Fig. 1, there is an upper and lower scale, one on each edge of the shield. It is necessary that the holes should be large enough to be easily legible under the prevailing conditions of fusion, and also that they shall be widely enough spaced in both directions to be easily read. It is also essential that a single little sensitive flame shall light up the whole exposed surface of the screen. This forces upon us the difficult problem of securing compactness. In the early models no other solution was seen than to restrict the instrument to a part of an octave, but a unique solution was finally found. This consists in alternating rows of widely different frequency as may be seen by observing the actual numbers of the adjacent lines on the screen in reading alternately on the upper and lower scale. The numbers on the upper scale are consecutive from 110 to 164, and the numbers on the lower scale from 165 to 219, the rows reading on one scale alternating with those reading on the other. To illustrate, if rows 150 and 151 were adjacent they would need to be separated by a wide space in order to be differentiated, because their movements are so nearly alike, but if they are separated by another row, for example the 205, the differentiation between the two original rows becomes clearer and the spaces between them may be materially reduced, for, when rows 150 and 151 stand approximately still and their individual dots stand out clear and distinct, row 205 moves so swiftly that it forms one continuous line or gray streak which has a most serviceable separating or framing effect for the adjacent rows. When the rows are arranged as shown on the scale, this differentiating, or framing effect will operate for each and every row that may be standing out for reading. This contrivance makes it possible to reduce the screen to about one-third of the size otherwise required, and still makes the reading more legible than it would

have been on a screen three times as large without some contrivance like this.

The sensitive light and sound transmitter.—A fundamental requirement in this principle of measurement is that the light shall be made intermittent through the action of sound waves. This may be accomplished in various ways. In the simplest arrangement an ordinary manometric capsule is used and the singer holds a funnel before his mouth in such a way as to effectively collect the vibrations. Acetylene gas supplied by a motorcycle tank is used for this sensitive flame. We have not yet determined the most effective form of capsule or the maximum upper and lower limit of its vibration response, but have found that this varies with numerous conditions, such as the vibration frequency, the volume, the smoothness, etc. of the tone. This capsule may be used in recording from such musical instruments as send a fairly concentrated volume of waves in one direction, such as tuning forks, wind instruments, reed instruments, and the siren. With all these it is, however, advantageous to use a Helmholtz or a Koenig resonator as a selector although it is not necessary in all cases. As a rule the shorter the speaking tube or horn, the less danger there is of interference in the sound waves.

While this mechanical transmission through a manometric capsule is for most purposes the simplest means, and is entirely satisfactory, especially in singing, we have electrical devices that have distinct advantages. The receiver of a microphone may be converted into a manometric capsule by building a gas chamber on the ear side and supplying it with a gas inlet and a jet nipple. The vibration of the receiver membrane controls the gas flame in the same way as in an ordinary capsule. The microphone transmitter is used with this as in ordinary speaking. The best type of commercial instrument that may be readily adapted for this purpose is the phonette or the acousticon made by the General Acoustic Company, New York. The acousticon known as type D seems to be the most serviceable.

While the electrical apparatus may be a little more delicate to handle it has the advantage that it is more sensitive and can be used for the recording of a tone which would not be strong enough to register in any other way. It also makes it possible to set this apparatus in front of the singer so that he may sing for a record

without being aware that a recording instrument is present in the room. The singer may be isolated in a quiet room or in familiar surroundings, in order not to be disturbed by the presence of another person and the main instrument. The measurement may even be made at any long distance covered by telephone connection, as all that is necessary is to put the microphone transmitter in front of the singer at one end of the telephone line, and connect it with the microphone receiver on the tonoscope at the other end.

When sound vibrations are strong enough completely to make and break the circuit, the ordinary telephone receiver may be used as a capsule in the manner just described. On certain musical instruments a mechanical interrupter resting on the resonating chamber of the instrument, for example, a violin may be used.

Under the same circumstances a vacuum tube may be used in place of the gas-flame capsule. The intermittent light is then caused by the interruption of the current in the primary circuit of an induction coil which has the vacuum tube in the secondary circuit.

If two simultaneous records are desired, one record may be taken on each side of the tonoscope. Indeed, four records may be taken simultaneously by using both the upper and the lower facets on the back and the face of the drum, there being doors on the case for this purpose.

The stroboscopic reading requires fairly complete darkness. To avoid darkening the room a hood (not shown in the figure) has been built to fit over the reading surface of the tonoscope. This hood forms a dark chamber and the inner surface, being bright, serves as an excellent reflector for the light. For intensive reading at a given point on the scale, a small sliding hood is made on the same principle. It has the advantage of centering the light upon the point of reading in the scale. A reflecting mirror (not shown in the figure) is used to distribute the light over the visible portion of the screen for ordinary use.

The siren.—For certain purposes it may be desirable to get a key-note or a standard pitch from the tonoscope itself. The dots on the screen were therefore made as holes. At the base of the front of the case is a siren blow-pipe supported on a horizontal carrier so that it may glide freely over the surface of the drum, while a pointer indicates on the scale just what hole-frequency is blown. This makes it possible to produce as siren tones all the tones from 110 to 219 by one-vibration steps, excepting those rows of holes

which happen to be closed by the contact with the balance wheel. The siren blow-pipe is connected with a compressed air tank or it may be blown directly by a mouth tube. A speaking tube is used to carry the sound to the observer's ear and the opening and closing of this tube by means of a clamp starts and stops the sound.

The siren tone is not a tone of good quality. But a beautiful tone may be produced by projecting a beam of light through the holes in the screen upon a selenium cell in circuit with a telephone receiver. It so happens that the fluctuation in the resistance of the selenium cell takes approximately the form of a sine curve, and that produces a tone of most remarkably clear and smooth timbre in the receiver. One may, however, use any sort of instrument for giving the standard tone, as the pitch of the instrument can be read off on the tonoscope at any moment.

The reading.—Although the reading is simple and direct, it is necessary to mention some of the underlying principles. The first task is to see which row stands still, or the nearest still. This row indicates the desired record and will be seen irresistibly the moment the tone is produced, because all other rows are blurred or in rapid motion. Having identified the line which stands still we must next know within what octave the tone lies. If, for example, row 128 stands still this may represent a tone of 64, 128, 256, 512 vibrations, or even higher. Now from 110 v.d. to 219 v.d. the correspondence is direct and the dots appear as actually spaced on the drum within an octave above this, the dots double in number and therefore stand only half as far apart; and, within the second octave above, they quadruple in number. It is therefore easy to see instantly from the spacing of the dots within which octave one is reading. If the spaces in row 128, *e.g.*, are one-half of the original the tone is 256 v.d.; if they are only one-fourth of the original steps, the tone is 512 v.d., etc.

But in fine reading we deal with fractions of vibrations. If instead of one row standing still, two rows move slowly in the opposite direction, the tone lies between these, and the fraction is determined by the relative rate of movement of the two rows. In a very accurate recording of instruments this may be done to a high degree of certainly by timing the movement with a stop watch over a considerable period of time. To do this we observe how many dot spaces are moving up or down and apply this general rule: if the ascend-

ing row has been counted, *add* the fraction of dot space per second; or, if the descending row has been counted, *subtract* it from the integral number of the row observed. It is best to count the faster moving of the two rows.

Sources of error.—There can be no time-error in the transformation of the sound wave into an illumination wave; they must synchronize, since one is the direct cause of the other. There can be no progressive change in the speed of the motor because if the motor does not run in step with the fork it must stop. The only possible error on the physical side lies in a tendency to pendular oscillation of the drum which may show a tendency to "hunt" when starting or when the current is too weak. By allowing a minute for the "finding" immediately after starting, and by securing a right adjustment of the strength of the current, this hunting movement may be reduced to an inappreciable or negligible quantity. The presence or absence of this source of error may, of course, be ascertained at any moment by registering the tone from a standard fork as a control. The limit of accuracy in the registering of the apparatus is therefore set by the limit of constancy in the driving fork. This fork being carefully balanced, firmly mounted, and kept in fairly constant temperature, shows a very high degree of constancy and compares favorably with a standard 100 v.d. fork.

But the main source of error lies in the reading, particularly of high tones. This need, however, be a source of error only in rapid reading. By making the tone long enough to observe the rate of fractional movement, one may secure any desired degree of accuracy in reading, as, *e.g.*, in registering a tuning fork, by timing the fractional movements of the dots for a sufficiently long time. In brief, without giving numerical records, we may say that the limit of accuracy in the use of the instrument is really set by the limit of accuracy of a tuning fork, the driving fork. For actual tests of accuracy in reading see Miles (6).

The use of the tonoscope.—The tonoscope furnishes us the first ready and, at the same time, reliable means of measuring directly the pitch of a tone as sung, spoken, or played with a musical instrument. Heretofore, graphic recording has been the only reliable method. This has the merit of accuracy but is entirely too indirect and laborious to be of general use in practical work. As we have seen, it registers the tone as sung or played under natural

conditions, and the record is simultaneous with the tone. The scope of its usefulness is therefore very great. It furnishes us an approach to countless problems both in pure and applied psychology. The psychology of tonal expression is a field practically unworked as compared with the psychology of the appreciation of tone, largely because we have not before had any convenient means of measurement.

A few concrete illustrations from the laboratory may be cited. In standardizing the pitch discrimination test (9) it was found necessary to compare the relative reliability of available instruments. Tuning forks, string instruments, reed instruments, wind instruments, and sirens were all tested by direct registration upon the tonoscope. Temperature coefficients, air pressure coefficients, and resonance coefficients were worked out by the same mode of registration. While most of these measurements could have been made in other ways, the tonoscope proved at least a good, labor-saving device.

The settling of disputed questions of pitch has been interesting. For example, there was a pitch discrepancy in the playing of the oboe and the French horn in a symphony orchestra. Each player was given an opportunity to register a specific tone in the tonoscope, and it was found that the oboe was playing consistently 1.5 v.d. flat. A vocal soloist had a tendency to flat relatively high notes. She observed the error and learned to make the right correction. A singer was practicing to eliminate an undesirable fluctuation of the pitch of the voice and was much helped in practicing before the tonoscope as before a mirror. In a recent article (10) I have described some measurements which at the present time could be made successfully only with the tonoscope.

There is a conspicuous place for the tonoscope in the musical conservatory. The ear of the singer or player is too generous because it seldom has any objective correction. The pupil persists in constant errors because there is no objective check on the ear. But the tonoscope does for the ear what the microscope does for the eye. It magnifies and objectifies to the eye, bringing out even small details of the pitch of the tone.

An actual experiment in training of the voice by the use of the instrument revealed among other facts the following (5): A group of six singers practicing daily for twelve days, part of the time

with the instrument and part of the time without it, showed that the average result of training with the instrument was superior to the average result of training without it, by forty-two per cent. in the ability to strike a tone, by fifty-five per cent. in the ability to sing musical intervals, and by twenty-six per cent. in the voluntary control of the voice in sharping or flatting; and the ability gained by virtue of the aid of the instrument was transferred in large part to ordinary singing.

The entire article by Dr. Miles in the present volume (6) should be regarded as supplementary to this description and particularly as furnishing illustrations of the use of the instrument. The general trend of usefulness of the tonoscope in the psychological laboratory, the musical conservatory, and other situations in which the registration of the pitch of tones is desirable may be indicated in a partial outline of measurements which may be made with it, as follows:

I. Striking a tone.
   1. Voluntary control of the pitch of a vocal or instrumental tone—the first and simplest test of ability to sound a given tone in true pitch.
   2. The effect on the pitch of a tone of conditions varied under control; *e.g.*, the character of the standard tone, the absolute pitch, the mode of tone production, distraction, practice, seeing the registration when producing the tone, information about previous errors, deliberate correction, etc.
   3. The pitch and reliability of the pitch of an instrument, as in tuning, testing, standardizing, and comparing instruments.

II. Sustaining a tone.
   1. Degree of accuracy or ability in holding a tone.
   2. Constant tendencies—sharp or flat.
   3. Artistic effects in singing a "constant" tone, as in pitch tremulo.
   4. Inflection of speech.

III. Minimal producible change.

A fundamental measure of discriminative action in the voluntary control of the pitch of a tone—a sort of psychophysic foot-rule which serves the same purpose on the motor side as the minimal producible change serves on the sensory side; *e.g.*, as a unit of measurement in the study of individual difference, or the effect of any other controlled variable.

IV. Tonal transition.

1. The mode and the accuracy of attack and release of tones in singing, in playing, or in inflection of speech (a) in measuring precision, (b) in registering some artistic effect, and (c) in musical or oratorical training.
2. Testing of instrument; *e.g.,* in proving that the piston pitch pipe is unfit for the sounding of a key-note because the note is necessarily attacked by a gradual sliding up to the key.

V. Tonal intervals.

Accuracy in producing musical intervals; *e.g.,* single steps, the natural scale, the chromatic scale, melody as in singing or playing of an air; (a) for the purpose of psychological or aesthetic study, or, (b) as a means of training in the musical conservatory.

VI. Transcribing of speech or musical records from the phonograph or any other recording instrument.

There are thus two quite distinct fields in which the tonoscope in its present form may be employed, namely, in the research laboratory and in the practical work of the musical conservatory.

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