the pleasing impression produced by such combinations was explained mathematically.

It is a law in music that the more simple the ratio between the number of vibrations in two sounds, the more perfect is the harmony. The simplest relation, of course, is 1 : 1, when the two sounds are said to be in unison. The next in order is 1 : 2. In sounding C and its 8th, for example, there are 48 vibrations of one to 96 of the other. These sounds can produce no discord, because the waves never interfere with each other, and the two sounds can be prolonged indefinitely, always maintaining the same relations. The combined impression is therefore continuous. The next in order is the 1st and 5th, their relations being 2 : 3. In other words, with the 1st and 5th, for two waves of the 1st there are three waves of the 5th. The two sounds may thus progress indefinitely, for the waves coincide for every second wave of the 1st and every third wave of the 5th. The next in order is the 3d. The 3d of C has the 8th of C for its 5th, and the 5th of C for its minor 3d. The 1st, 3d, 5th and 8th form the common major chord; and the waves of each tone blend with each other at such short intervals of time that the ear experiences a continuous impression, and no discord is appreciated. This explanation of the common major chord illustrates the law that the smaller the ratio of vibration between different tones, the more perfect is their harmony. Sounded with the 1st, the 4th is more harmonious than the 3d; but its want of harmony with the 5th excludes it from the common chord. The 1st, 4th and 8th are harmonious, but to make a complete chord the 6th must be added.

Discords.—A knowledge of the mechanism of simple accords leads naturally to a comprehension of the rationale of discords. The fact that certain combinations of musical notes produce a disagreeable impression was ascertained empirically, with no knowledge of the exact cause of the dissonance; but the mechanism of discord may now be regarded as settled.

The sounds produced by two tuning-forks giving precisely the same number of vibrations in a second are in perfect unison. If one of the forks be loaded with a bit of wax, so that its vibrations are slightly reduced, and if both be put in vibration at the same instant, there is discord. Taking the illustration given by Tyndall, it may be assumed that one fork has 256, and the other, 255 vibrations in a second. While these two forks are vibrating, one is gradually gaining upon the other; but at the end of half a second, one will have made 128 vibrations, while the other will have made 127½. At this point the two waves are moving in exactly opposite directions; and as a consequence, the sounds neutralize each other, and there is an instant of silence. The perfect sounds, as the two forks continue to vibrate, are thus alternately re-enforced and diminished, and this produces what is known in music as beats. As the difference in the number of vibrations in a second is one, the instants of silence occur once in a second; and in this illustration the beats occur once a second. Unison takes place when two sounds can follow each other indefinitely, their waves blending perfectly; and dissonance is marked by successive beats, or pulses. If the forks be loaded so that one will vibrate 240 times in a second, and the other 234, there will be six times in a second

when the interference will be manifest; or in other words in ⅙ of a second, one fork will make 40 vibrations, while the other is making 39. This will give 6 beats in a second. From these experiments the law may be deduced, that the number of beats produced by two tones not in harmony is equal to the difference between the two rates of vibration. An analogous interference of undulations is observed in optics, when waves of light are made to interfere and produce darkness.

It is evident that the number of beats will increase as two discordant notes are produced higher and higher in the scale. According to Helmholtz, the beats can be recognized up to 132 in a second. Beyond that point they become confused, and there is only a general sensation of dissonance. Beats, then, are due to interference of sound-waves. There is no interference of the waves of tones in unison, provided that waves start at the same instant; the intensity of the sound being increased by re-enforcement. The differences between the 1st and 8th, the 1st and 5th, the 1st and 3d, and other harmonious combinations, is so great that there are no beats and no discord, the more rapid waves re-enforcing the harmonics of the primary sound. It is important to remember in this connection, that resultant tones are equal to the difference in the rates of vibration of two harmonious tones. Taking a note of 240 vibrations, and its 5th, with 360 vibrations, these two have a difference of 120, which is the lower octave of the 1st and is an harmonious tone.

It is evident that the laws just stated are applicable to overtones, resultant tones and additional tones, which, like the primary notes, have their beats and dissonances.

Tones by Influence.—After what has been stated in regard to the laws of musical vibrations, it will be easy to comprehend the production of sounds by influence. If a key of the piano be lightly touched, so as to raise the damper but not to sound the string, and then a note be sung in unison, the string will return the sound, by the influence of the sound-waves of the voice. The sound thus produced by the string will have its fundamental tone and overtones; but the series of overtones will be complete, for none of the nodes are abolished, as in striking or plucking a string at any particular point. If instead of a note in unison, any of the octaves be sounded, the string will return the exact note sung; and the same is true of the 3d, 5th etc. If a chord in harmony with the undamped string be struck, this chord will be exactly returned by influence. In other words, a string may be made to sound by influence, its fundamental tone, its harmonics and harmonious combinations. To carry the observation still farther, the string will return, not only a note of its exact pitch and its harmonics, but notes of the peculiar quality of the primary note. This is a very important point in its applications to the physiology of hearing and can be readily illustrated. Taking identical notes in succession, produced by the voice, trumpet, violin, clarinet or any other musical instrument, it can easily be noted that the quality of the note, as well as the pitch, is rendered by a resounding string; and the same is true of combinations of notes. These laws of tones by influence have been

illustrated by strings merely for the sake of simplicity; but they have a more or less perfect application to all bodies capable of producing musical tones, except that some are thrown into vibration with more difficulty than others.

A thin membrane, like a piece of bladder or thin rubber, stretched over a circular orifice, such as the mouth of a wide bottle, may readily be tuned to a certain note. When arranged in this way, the membrane can be made to sound its fundamental note by influence. In addition, the membrane, like a string, will divide itself so as to sound the harmonics of the fundamental, and it will likewise be thrown into vibration by the 5th, 3d etc., of its fundamental, thus obeying the laws of vibrations of strings, although the harmonic sounds are produced with greater difficulty.

The account just given of some of the laws of sonorous vibrations and their relations to musical effects and combinations, although by no means complete, may seem rather extended for a work on physiology; but it should be borne in mind that the mechanism of the appreciation of musical sounds includes the entire physiology of audition. This subject can not be comprehended without a general knowledge of the physics of sound and of some of the laws of harmony; for not only is there a perception of single notes by the auditory apparatus, but the most intricate combinations of sounds in harmony are all appreciated together and at one and the same instant, as will be seen in studying the action and uses of different parts concerned in audition. Many of the laws of musical combinations are directly applicable to the physiology of hearing.

Uses of Different Parts of the Middle Ear.

The uses of the pavilion and of the external auditory meatus are sufficiently apparent. The pavilion serves to collect the waves of sound, and probably it inclines them toward the external meatus as they come from various directions. Although this action is simple, it has a certain degree of importance, and the various curves of the concavity of the pavilion tend more or less to concentrate sonorous vibrations. Such has long been the opinion of physiologists, and this seems to be carried out by experiments in which the concavities of the external ear have been obliterated by wax. There probably is no resonance or vibration of much importance until the waves of sound strike the membrana tympani. The same remarks may be made with regard to the external auditory meatus. It is not known precisely how the obliquity and the curves of this canal affect the waves of sound, but it is probable that the deviation from a straight course protects, to a certain extent, the tympanic membrane from impressions that might otherwise be too violent.

Structure of the Membrana Tympani.—The general arrangement of the membrana tympani has already been described in connection with the topographical anatomy of the auditory apparatus. The membrane is elastic, about the thickness of ordinary gold-beater's skin, and is subject to various degrees of tension by the action of the muscles of the middle ear and under

different conditions of atmospheric pressure within and without the tympanic cavity. Its form is nearly circular; and it has a diameter in the adult, according to Sappey, of a little more than $\frac{2}{3}$ of an inch (10 to 11 mm.) vertically and about $\frac{2}{3}$ of an inch (10 mm.) antero-posteriorly. The excess of the vertical over the horizontal diameter is about $\frac{1}{50}$ of an inch (0·5 mm.)

The periphery of the tympanic membrane is received into a little ring of bone, which may be separated by maceration in early life, but which is consolidated with the adjacent bony structures in the adult. This bony ring is incomplete at its superior portion, but aside from this, it resembles the groove which receives the crystal of a watch. At the periphery of the membrane, is a ring of condensed, fibrous tissue, which is received into the bony ring. This ring also presents a break at its superior portion.

The concavity of the membrana tympani presents outward, and it may be increased or diminished by

Fig. 268.—*Right membrana tympani, seen from within.* From a photograph, and somewhat reduced (Rüdinger).

1, head of the malleus, divided; 2, neck of the malleus: 3, handle of the malleus, with the tendon of the tensor tympani muscle: 4, divided tendon of the tensor tympani; 5, 6, portion of the malleus between the layers of the membrana tympani; 7, outer (radiating) and inner (circular) fibres of the membrana tympani; 8, fibrous ring of the membrana tympani; 9, 14, 15, dentated fibres, discovered by Gruber; 10, posterior pocket; 11, connection of the posterior pocket with the malleus; 12, anterior pocket; 13, chorda tympani nerve.

the action of the muscles of the middle ear. The point of greatest concavity, where the extremity of the handle of the malleus is attached, is called the umbo. Upon the inner surface of the membrane are two pouches, or pockets. One is formed by a small, irregular, triangular fold, situated at the upper part of its posterior half and consisting of a process of the fibrous layer. This, which is called the posterior pocket, is open below and extends from the posterior upper border of the membrane, to the handle of the malleus, which it assists in holding in position. "After it has been divided, the bone is much more movable than before" (Tröltsch). The anterior pocket is lower and shorter than the posterior. It is formed by a small, bony process turned toward the neck of the malleus, by the mucous membrane, by the bony process of the malleus, by its anterior ligament, the chorda tympani and the anterior tympanic artery. The handle of the malleus is inserted
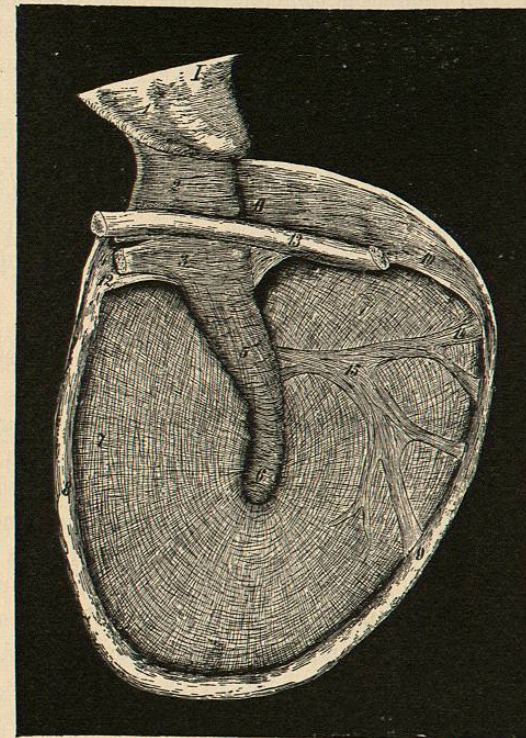
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between the two layers of the fibrous structure of the membrana tympani and occupies the upper half of its vertical diameter, extending from the periphery to the umbo.

The membrana tympani, though thin and translucent, presents three distinct layers. Its outer layer is a very thin extension of the integument lining the external meatus, presenting, however, neither papillæ nor glands. The inner layer is a delicate continuation of the mucous membrane lining the tympanic cavity and is covered by tessellated epithelial cells. The fibrous portion, or lamina propria, is formed of two layers. The outer layer consists of fibres radiating from the handle of the malleus to the periphery. These are best seen near the centre. The inner layer is composed of circular fibres, which are most abundant near the periphery and diminish in number toward the centre.

The color of the membrana tympani, when it is examined with an aural speculum by daylight, is peculiar, and it is rather difficult to describe, as it varies in the normal ear in different individuals. Politzer described the membrane, examined in this way, as translucent, and of a color which "most nearly approaches a neutral gray, mingled with a weaker tint of violet and light yellowish-brown." This color is modified, in certain portions of the membrane, by the chorda tympani and the bones of the ear, which produce some opacity. The entire membrane in health has a soft lustre. In addition there is seen, with proper illumination, a well-marked, triangular cone of light, with its apex at the end of the handle of the malleus, spreading out in a downward and forward direction, and $\frac{1}{16}$ to $\frac{1}{8}$ of an inch (1·6 to 2·1 mm.) broad at its base. This appearance is regarded by physiologists as very important, as indicating a normal condition of the membrane. It is undoubtedly due to reflection of light and not to a peculiar structure of that portion of the membrane upon which it is seen.

Uses of the Membrana Tympani.—It is unquestionable that the membrana tympani is very important in audition. In cases of disease in which the membrane is thickened, perforated or destroyed, the acuteness of hearing is always more or less affected. That this is in great part due to the absence of a vibrating surface for the reception of waves of sound, is shown by the relief which is experienced by those patients who can tolerate the presence of an artificial membrane of rubber. As regards the mere acuteness of hearing, aside from the pitch of sounds, the explanation of the action of the membrane is very simple. Sonorous vibrations are not readily transmitted through the atmosphere to solid bodies, like the bones of the ear; and when they are thus transmitted they lose considerably in intensity. When, however, the aërial vibrations are received by a membrane, under the conditions of the membrana tympani, they are transmitted with very little loss of intensity; and if this membrane be connected with solid bodies, like the bones of the middle ear, the vibrations are readily conveyed to the sensory portions of the auditory apparatus. The parts composing the middle ear are well adapted to the transmission of sonorous waves to the auditory nerves. The membrane of the tympanum is delicate in structure, stretched to the proper degree of

tension, and vibrates under the influence of the waves of sound. Attached to this membrane, is the angular chain of bones, which conducts its vibrations, like the bridge of a violin, to the liquid of the labyrinth. The membrane is fixed at its periphery and has air upon both sides, so that it is under favorable conditions for vibration.

A study of the mechanism of the ossicles and muscles of the middle ear shows that the membrana tympani is subject to certain physiological variations in tension, due to the contraction of the tensor tympani. It is also evident that this membrane may be drawn in and rendered tense by exhausting or rarefying the air in the drum. If the mouth and nose be closed and an attempt be made to breathe forcibly by expanding the chest, the external pressure tightens the membrane. In this condition the ear is rendered insensible to grave sounds, but high-pitched sounds appear to be more intense. If the tension be removed, as may be done by an act of swallowing, the grave sounds are heard with normal distinctness. This experiment, tried at a concert, produces the curious effect of abolishing a great number of the lowest tones, while the shrill sounds are heard very acutely. The same phenomena are observed when the external pressure is increased by descent in a diving-bell.

Undoubted cases of voluntary contraction of the tensor tympani have been observed by otologists; and in these, by bringing this muscle into action, the limit of the perception of high tones is greatly increased. In two instances of this kind, recorded by Blake, the ordinary limit of perception was found to be three thousand single vibrations, and by contraction of the muscle, this was increased to five thousand single vibrations.

The concave form of the membrana tympani and the presence of a bony process between its layers, which is part of the chain of bones of the middle ear, are conditions under which it is impossible that it should have a single, fundamental tone. This has been shown by experiments with stretched membranes depressed in their central portion by means of a solid rod. No membrane can have a single, fundamental tone unless it be in a condition of uniform tension, like a string, and this is impossible in the membrana tympani. Nevertheless the membrana tympani repeats sounds by influence, and it is capable of repeating in this way a much greater variety of sounds than if it had itself a fundamental tone and were capable of a uniform degree of tension. This has been shown by experiments with stretched, elastic membranes made to assume a concave form. If the membrana tympani had a single, fundamental tone, it would vibrate by influence only with certain tones in unison with it, and the overtones would be eliminated. It would then act like a resonator closed by a membrane, and the tone with which it happened to be in unison would overpower all other tones. The fact is that all tones, the vibrations of which reach the membrane, are appreciated at their proper value as regards intensity. Again, if the membrana tympani had its own fundamental tone, it would have overtones of the fundamental, which would produce errors and confusion in auditory appreciation. The chain of bones, also, attached to the membrane, acts as a damper and prevents the persist-

ence of vibrations after the waves of sound cease in the air. This provision enables rapid successions of sounds to be distinctly and acurately repeated.

The arrangement of the muscles and bones of the middle ear is such that the tension of the membrana tympani may be regulated and graduated with great nicety. It does not seem to be necessary to perfect audition that this should be done for every single note or combination of notes, but the membrane probably is brought by voluntary effort to a definite degree of tension for notes within a certain range as regards pitch or for successions and progressions of sounds in a particular key. As far as the consciousness of this muscular action is concerned, it may be revealed only by the fact of the correct appreciation of certain musical sounds. Some persons can educate the ear so as to acquire what is called the faculty of absolute pitch; that is, without the aid of a tuning-fork or any musical instrument, they can give the exact musical value of any given note. A possible explanation of this is that such persons may have educated the muscles of the ear so as to put the tympanic membrane in such a condition of tension as to respond to a given note and to recognize the position of this note in the musical scale. Finally, an accomplished musician, in conducting an orchestra, can by a voluntary effort, direct his attention to certain instruments and hear their notes distinctly, separating them from the general volume of sound, can distinguish the faintest discords and can designate a single instrument making a false note.

Destruction of both tympanic membranes does not necessarily produce total deafness, although this condition involves considerable impairment of hearing. So long as there is simple destruction of these membranes, the bones of the middle ear and the other parts of the auditory apparatus being intact, the waves of sound are conducted to the auditory nerves, although this is done imperfectly. In a case reported by Astley Cooper, one membrana tympani was entirely destroyed, and the other was nearly gone, there being some parts of its periphery remaining. In this person the hearing was somewhat impaired, although he could distinguish ordinary conversation without much difficulty. Fortunately he had considerable musical taste, and it was ascertained that his musical ear was not seriously impaired; "for he played well on the flute and had frequently borne a part in a concert. I speak this, not from his authority only, but also from that of his father, who is an excellent judge of music, and plays well on the violin: he told me, that his son, besides playing on the flute, sung with much taste, and perfectly in tune."

There is an important consideration that must be kept in view in studying the uses of any distinct portion of the auditory apparatus, like the membrana tympani. This membrane, like all other parts of the apparatus, except the auditory nerves themselves, has simply an accessory action. If the regular waves of a musical sound be conveyed to the terminal filaments of the auditory nerves, these waves make their impression and the sound is correctly appreciated. It makes no difference, except as regards intensity, how these waves are conducted; the sound is appreciated by the impression made upon the nerves, and the nerves only. The waves of sound are not like the waves of light, refracted, decomposed, perhaps, and necessarily brought to a

focus as they impinge upon the retina; but as far as the action of the accessory parts of the ear are concerned, the waves of sound are unaltered; that is, the rate of their succession remains absolutely the same, though they be reflected by the concavities of the concha and repeated by the tympanic membrane. Even if it be assumed that the membrane under normal conditions repeats musical sounds by vibrations produced by influence, and that sounds are exactly repeated, the position of these sounds in the musical scale is not and can not be altered by the action of any of the accessory organs of hearing. The fact that a person may retain his musical ear with both membranes destroyed is not really an argument against the view that the membrane repeats sounds by influence; for if musical sounds or noisy vibrations be conducted to the auditory nerves, the impression produced must of necessity be dependent exclusively upon the character, regularity and number of the sonorous vibrations. And, again, the physical laws of sound teach that a membrane, like the membrana tympani, must reproduce sounds with which it is more or less in unison much more perfectly than discordant or irregular vibrations. In a loud confusion of noisy sounds, one can readily distinguish melody or harmony, even when the vibrations of the latter are comparatively feeble.

It has been shown that the appreciation of the pitch of sounds bears a certain relation to the degree of tension of the tympanic membrane. When the membrane is rendered tense, there is insensibility to low notes. When the membrane is brought to the highest degree of tension by voluntary contraction of the tensor tympani, the limit of appreciation of high notes may be raised from three thousand to five thousand vibrations. It is a fact in the physics of the membrana tympani that the vibrations are more intense the nearer the membrane approaches to a vertical position; and it has been observed that the membrane has a position more nearly vertical in musicians than in persons with an imperfect musical ear (Tröltsch).

Experiments have shown that the tympanic membrane vibrates more forcibly when relaxed than when it is tense. In certain cases of facial palsy, in which it is probable that the branch of the facial going to the tensor tympani was affected, the ear has been found painfully sensitive to powerful impressions of sound. This probably has no relation to pitch, and most sounds that are painfully loud are comparatively grave. Artillerists are in danger of rupture of the membrana tympani from sudden concussions. To guard against this injury, it is recommended to stop the ear, draw the shoulder up against the ear most in danger, and particularly to inflate the middle ear after Valsalva's method. "This method consists in making a powerful expiration, with the mouth and nostrils closed" (Tröltsch).

Mechanism of the Ossicles of the Ear.—The ossicles of the middle ear, in connection with the muscles, have a twofold office: First, by the action of the muscles the membrana tympani may be brought to different degrees of tension. Second, the angular chain of bones serves to conduct sonorous vibrations to the labyrinth. It must be remembered that the handle of the malleus is closely attached to the membrana tympani, especially near its