PHYSICS ON STAGE 3

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APPROACHING THE PHYSIOLOGICAL CONSTRUCTION OF THE HUMAN EAR

ILIAS KALOGIROU
GREECE

e-mail: mail@ekfe.ilei.sch.gr

A REPRESENTATION OF THE PHYSIOLOGICAL CONSTRUCTION OF THE HUMAN EAR

A FULL TEXT

This apparatus has been designed to demonstrate the physiological construction of the human ear.

A loudspeaker transmits sound which is picked up by the outer ear, represented in the model by an ice-cream cone, and the sound is then guided into a plastic cylinder representing the auditory canal. The canal magnifies the sound by a factor of two before it reaches the ear drum (tympanic membrane) which vibrates in sympathy with the frequency of the sound reaching it. The membrane has been made out of pieces cut from an elastic glove in this model.

The hammer bone, (malleus), made from the top of a liquid soap bottle, is attached to the membrane and is, in turn, attached to the anvil (incus) – again formed from the cap of a liquid soap bottle – which is connected to the stirrup (stapes), depicted here by a toy spade.

The Cochlea

The cochlea in the human ear is a spiral tube with two and a half coils, but here it has been made from a straight Plexiglas cylinder in order to show its basic construction and main structures. The cochlea consists of the vestibular and tympanic ramps together with the cochlear duct which is triangular in cross section. It lies between the basilar membrane and Reissner's membrane. On the basilar membrane are the hair cells. These end in hairs which penetrate the tectorial membrane. The basilar membrane – made out of transparent film material – is narrow and under tension at one end but wide and slack at the other.

The end of the cochlea which is connected to the auditory ossicles contains the oval membrane and the round membrane below it. The other end of the cochlea is closed. When the stirrup strikes the oval window once, it presses on the fluid in the cochlea. This disturbance extends the entire length of the basilar membrane and via the helicotrema reaches the round window which bulges outwards as the disturbances in the fluid are dispersed.

However, if the number of impulses increases rapidly, the fluid is unable to disperse the energy in the same way and interacts instead with the basilar membrane as this is the quickest and easiest route to take. As a result, the basilar membrane vibrates up and down, exciting the hair cells. Thus, as the basilar membrane closes on the tectorial membrane in a similar way as the closing blades of a pair of scissors, the hairs bend and, in a way which is still unknown, produce electrical signals which are immediately transmitted to the brain via the acoustic nerve. Research has shown that high frequencies – such as a woman's voice, birdsong or the sound of a siren – activate the tense, narrow region of the basilar membrane while low frequencies such as a male voice or a frog's croak activate the wide, slack part of the membrane. In other words, different regions of the membrane are stimulated by different frequencies.

Principles of physics demonstrated by the process of hearing.

1. The auditory canal acts as a resonator which can double the pressure of air, particularly in the frequency range of 3 – 4 KHz
2. The three auditory ossicles combine to form a lever which increases the mechanical force by a factor of 1.3
3. The force from the stapes acts on the oval window which has an area approximately 15 times smaller than that of the tympanic membrane. Therefore, the fluid in the cochlea transfers a greater pressure than that of the stapes through the oval window
4. The increased pressure in the fluid in the cochlea is transferred unaltered in accordance with Pascal's Law

The working of the basilar membrane.

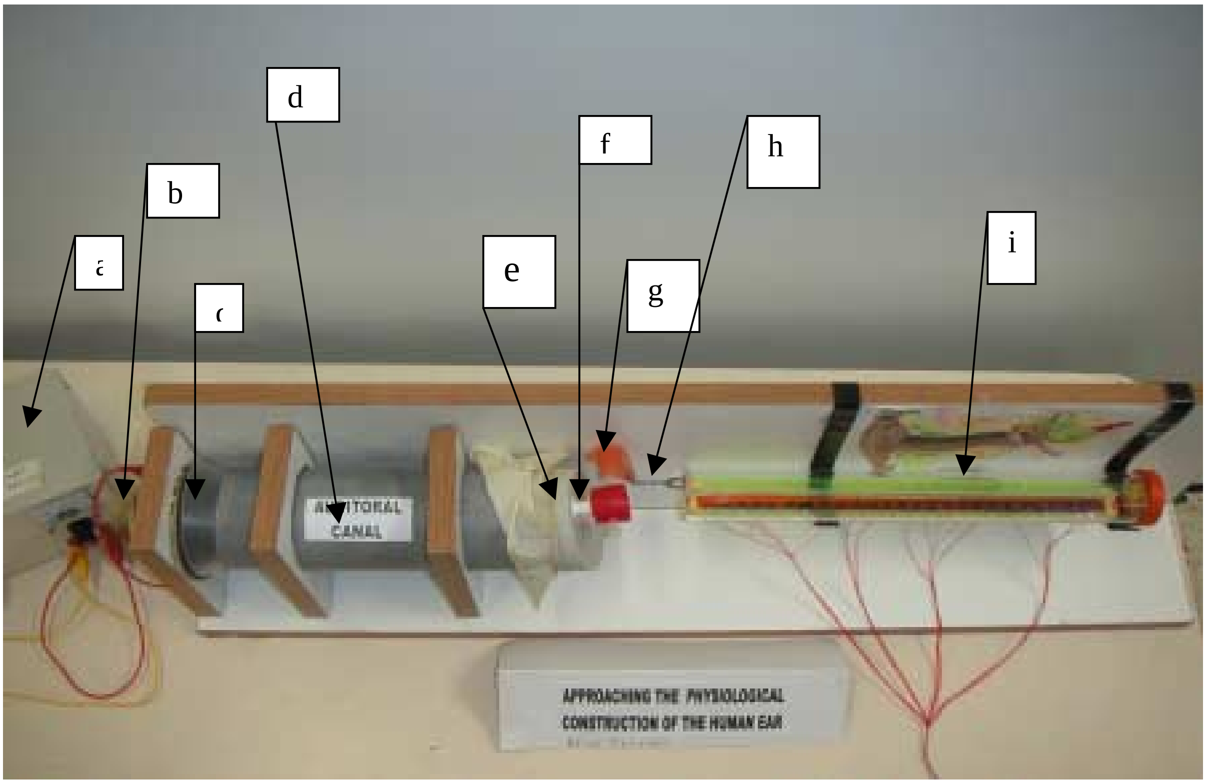
In the search for an analogy to demonstrate the working of the basilar membrane we decided to use a series of strips of hoop iron of increasing length.

The natural resonant frequency of the shortest strip is greater than that of the longest. If the strips, which are held rigid at one end, are subjected to a vibration then different strips will resonate according to the frequency of the vibration applied. The vibration is applied with an ordinary variable speed electric drill and an eccentric drive. From the sound produced by the drill one can understand when the frequency of rotation increases and observe that the shorter irons vibrate in harmony as a result. The free ends of the hoop irons have been bent through ninety degrees to form a hook shape. These represent the hair cells. As the metal strips vibrate the hair cells come into contact with aluminium foil attached to a wooden batten placed above them and which represents the tectorial membrane. When the iron touches the foil an electric circuit is closed which lights up a series of lamps mounted on a plastic channel representing the auditory nerve. The lamps turn on and off to show the transfer of the electric signal to the brain. In this way the mechanical energy of the moving strips of hoop iron is transformed into an electric signal which is sent to the brain.

As has been mentioned, when the hairs bend their cells produce an electric signal in a way which is as yet not fully understood. For that reason a simple electrical circuit with lamps is used to indicate the transformation of mechanical energy into electrical signals.

B CONSTRUCTION DETAILS

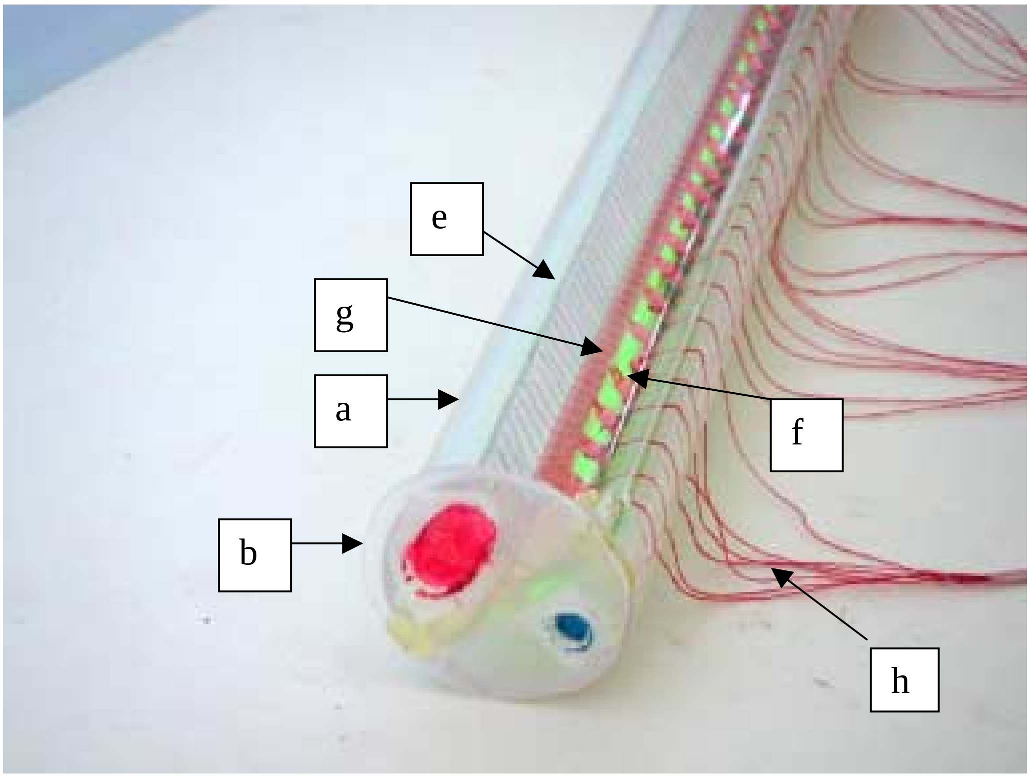
PART 1: A REPRESENTATION OF THE CONSTRUCTION OF THE HUMAN EAR
This apparatus seems in photograph 1.



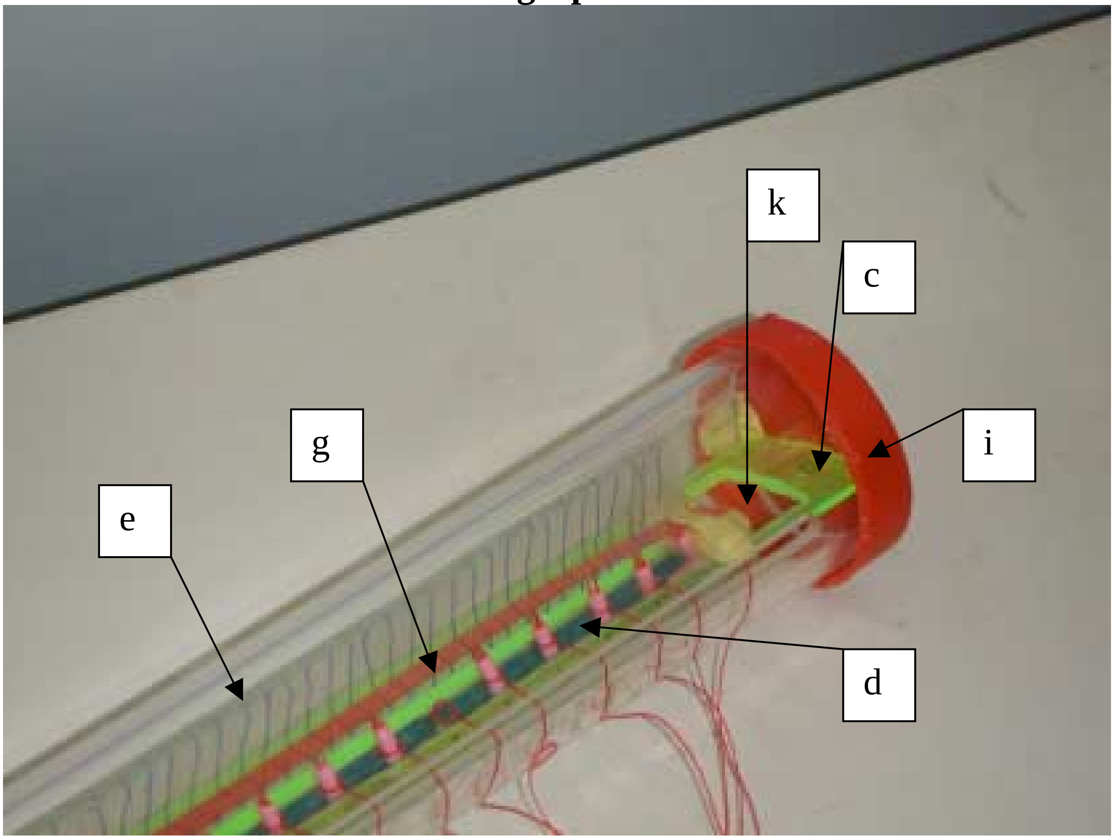
Photograph 1.

a: Low frequency signal generator with amplifier.
b: Loudspeaker
c: Ice-cream plastic cone
d: Plastic cylinder (diameter 75 mm, length 23 cm).
e: Piece from an elastic glove
f: Cap of a liquid soap bottle
g: Top of a liquid soap bottle
h: The handle of a toy spade
i: Cochlea (see photograph 2).

The construction of the cochlea seems in photographs 2 and 3.



Photograph 2

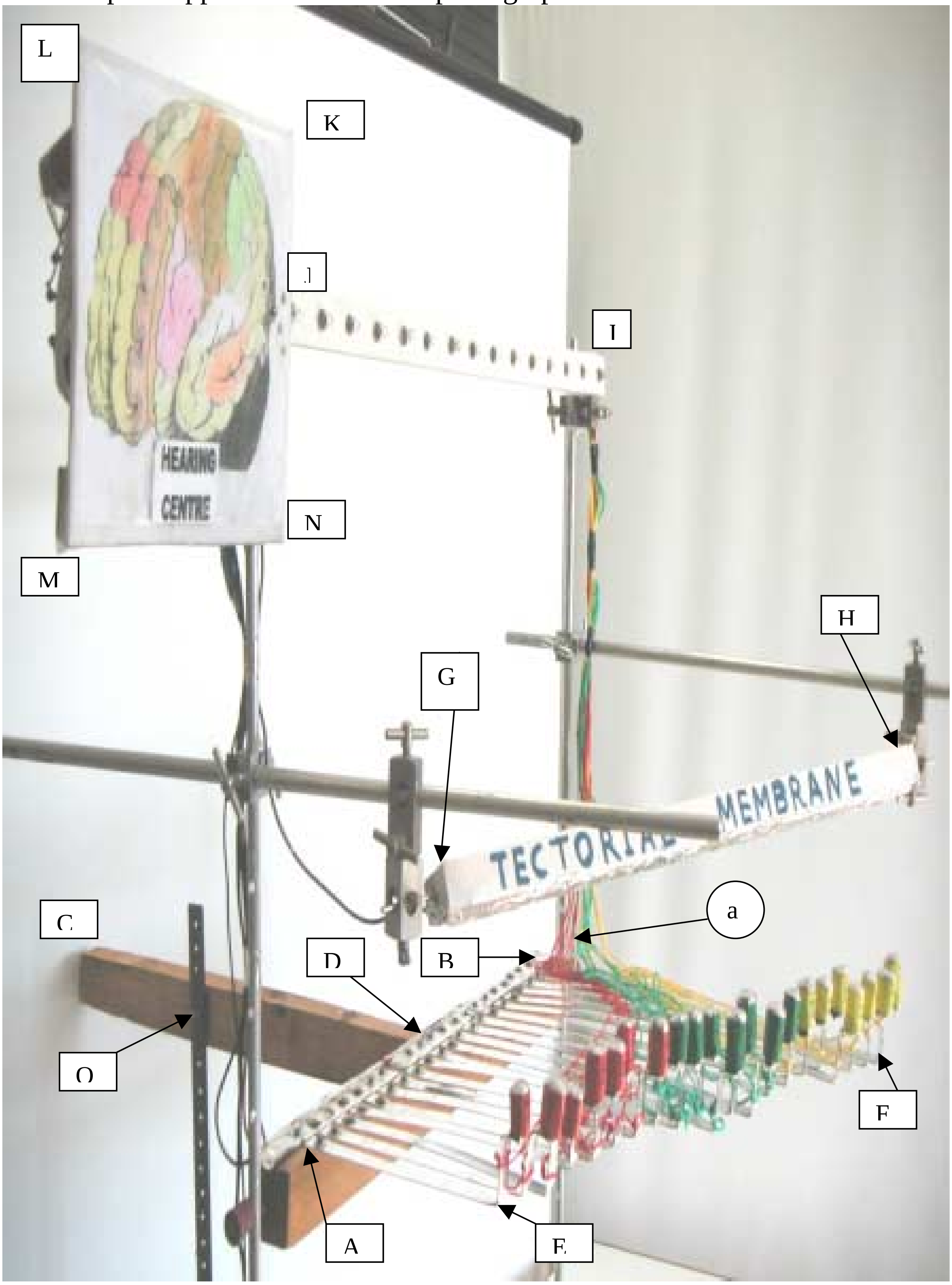


Photograph 3

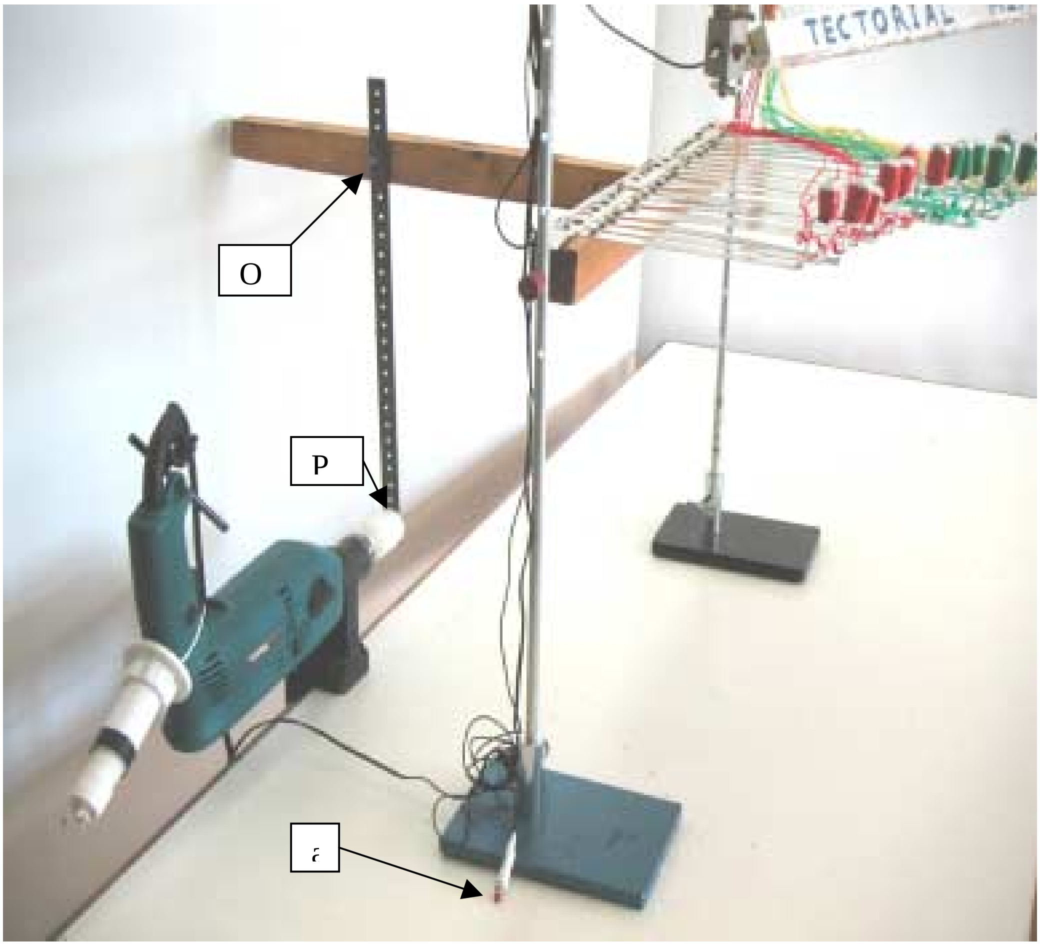
a: Plexiglas cylinder (diameter 4cm and length 31cm).
b: Plastic disk with two holes [the first is oval window (piece of elastic glove painted red) and the other is round window (piece of elastic glove painted blue)].
c: Ruler (one part of this ruler has been cut in order to put and glue transparent film.). The width of ruler is equal to the diameter of Plexiglas cylinder.
d: A piece of transparent film painted blue (basilar membrane is represented by this film.)
e: Half a ruler (Reissner’s membrane is represented by this ruler)
f: Small plastic baton with hairs from toothbrush on top(hair cell is represented by this baton).
g: A piece of transparent film painted orange (tectorial membrane is represented by this film)
h: Threads(nerve fibres are represented by these).
i: Plastic cover
k: Helicotrema

PART 2: A MECHANICAL MODEL TO DEMONSTRATE THE WORKING OF THE BASILAR MEMBRANE

The complete apparatus is shown in photographs 4 & 5.



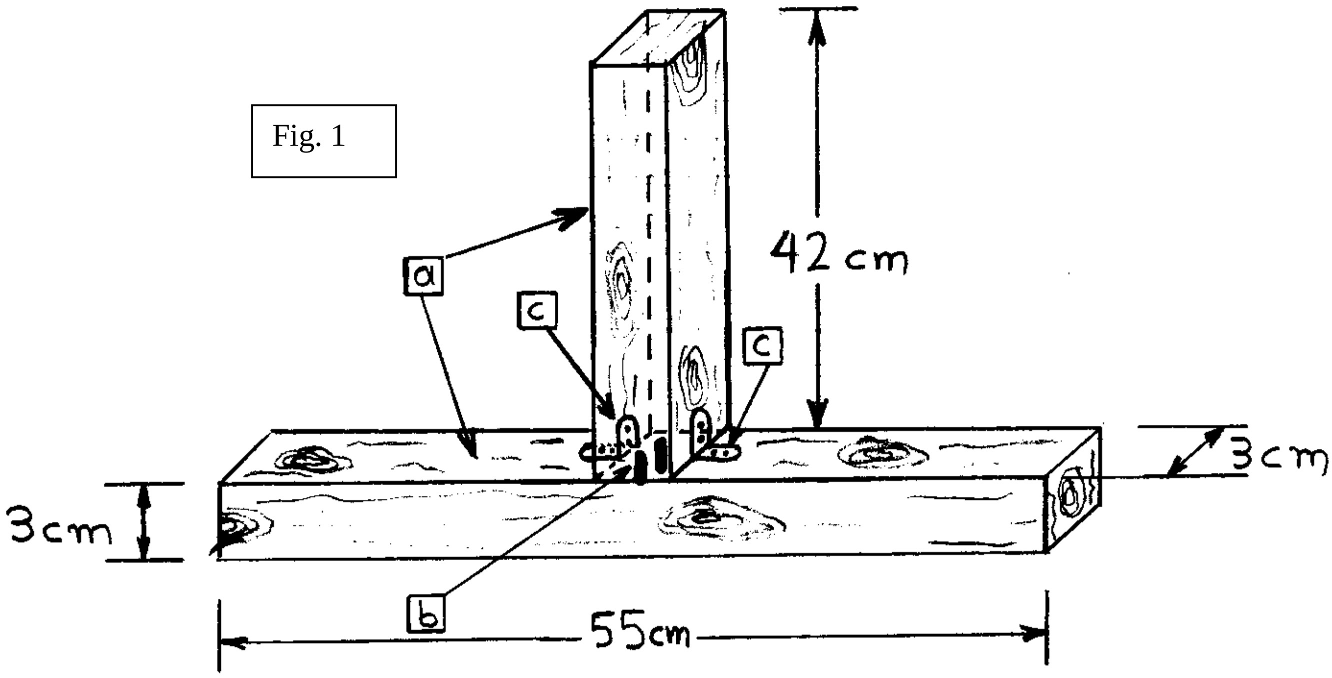
Photograph 4



Photograph 5

1. Construction of wooden "T- piece" (AB and CD in photograph 4). See fig. 1

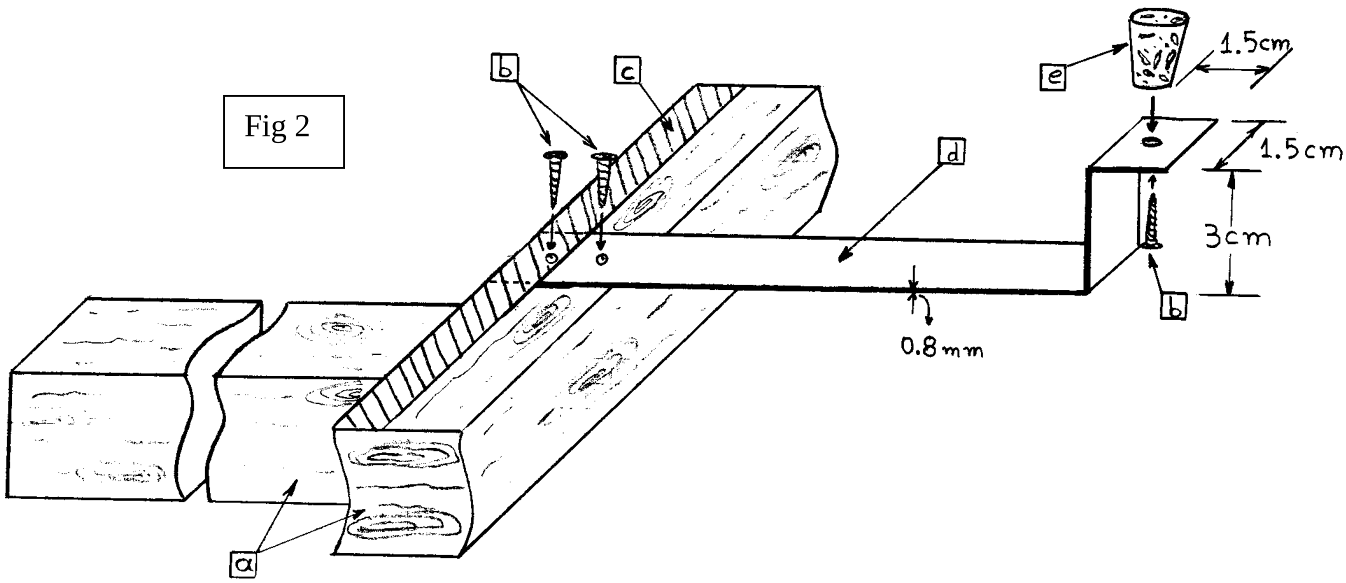
Fig. 1



a: Two wooden battens
b: Two wooden pegs
c: Two metal brackets to strengthen the joint between the battens

2. Fastening the hoop iron to the “ T- piece” (see fig.2) (AE,…, BF in photograph 4)

Fig 2



a: Wooden “T-piece”
b: Screws
c: Aluminum foil. This foil connects all the hoop irons of the same color.
d: One of 21 hoop irons. The whole surface of every hoop iron is covered with aluminum self- adhesive tape. This tape also covers the cork e. As a result, the hoop iron and cork combined form an electrical conductor. Colored adhesive tape is then wound around each cork. The first group of seven corks with yellow (low frequencies), the second with green (middle frequencies) and the third group with red tape(high frequencies).
e: Bottle cork.

3. The representation of basilar membrane of cochlea. (See fig. 3)

Fig. 3 contains fig. 1 and fig. 2. Fig.3 shows the complete apparatus which represents the basilar membrane of the cochlea.

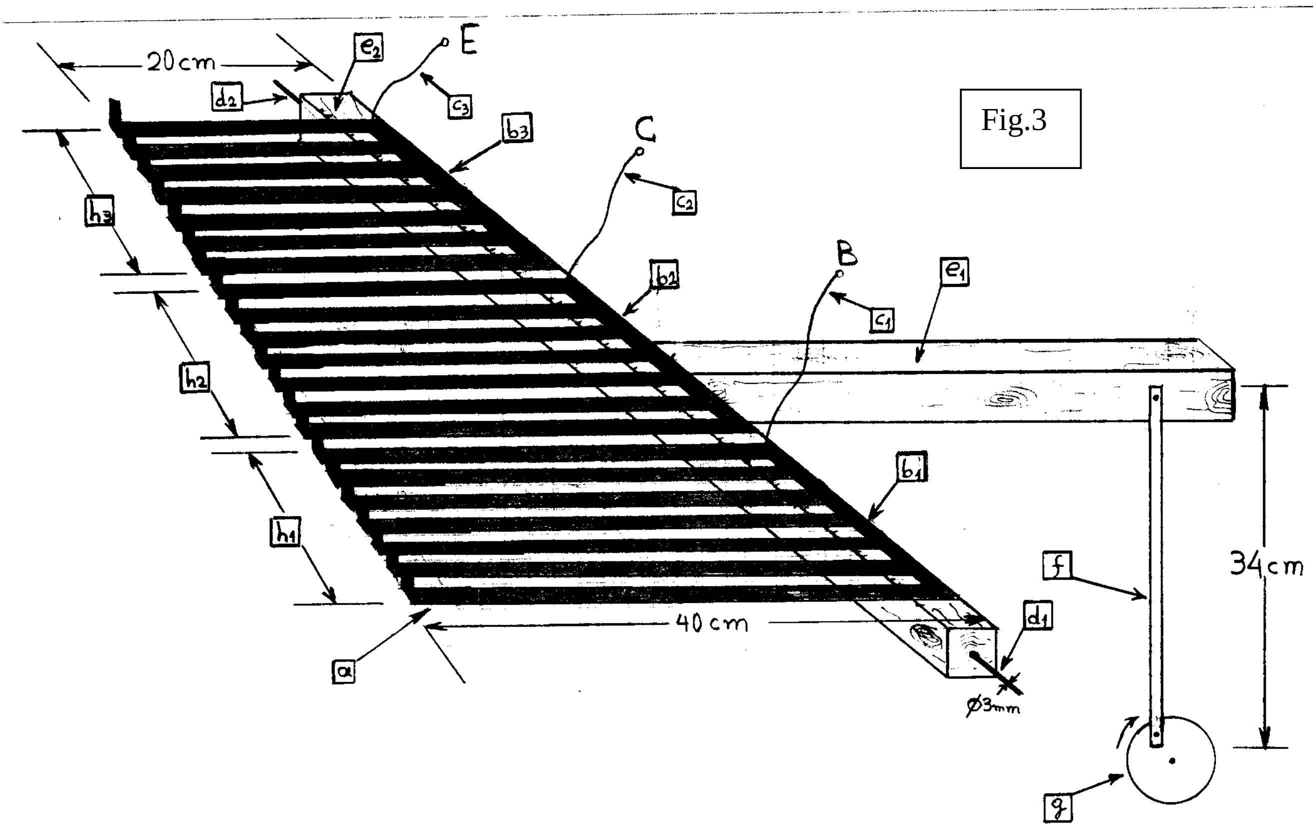


Fig.3

a: One of 21 hoop irons.
b_1, b_2,b_3: Strips of aluminum foil (each one for every group of seven hoop irons).
c_1, c_2, c_3 : leads (the points B,C,E, must be connected to points B, C, E respectively in fig 5)
d_1, d_2,: metal axles of length 8mm each (length of 4mm is in the wood.).
e_1, e_2 : Wooden " T- piece".
f: Steel Strip (dimensions : 34cm X 2cm X 3mm)
g: This cylinder is made from "Ertalon" a strong plastic material and is rotated by the drill (see c, fig 7).
h1: Corks with yellow tape
h2: Corks with green tape
h3: Corks with red tape

Note

This apparatus can also be used for experiments concerning resonance. Students hold the "T-piece" and try to make each hoop iron vibrate by changing the frequency of oscillation they apply to part e_1 of the "T-piece" with one hand, holding the apparatus steady with the other hand.

4. The wooden batten which represents the tectorial membrane (see GH in photograph 4), fig.4.

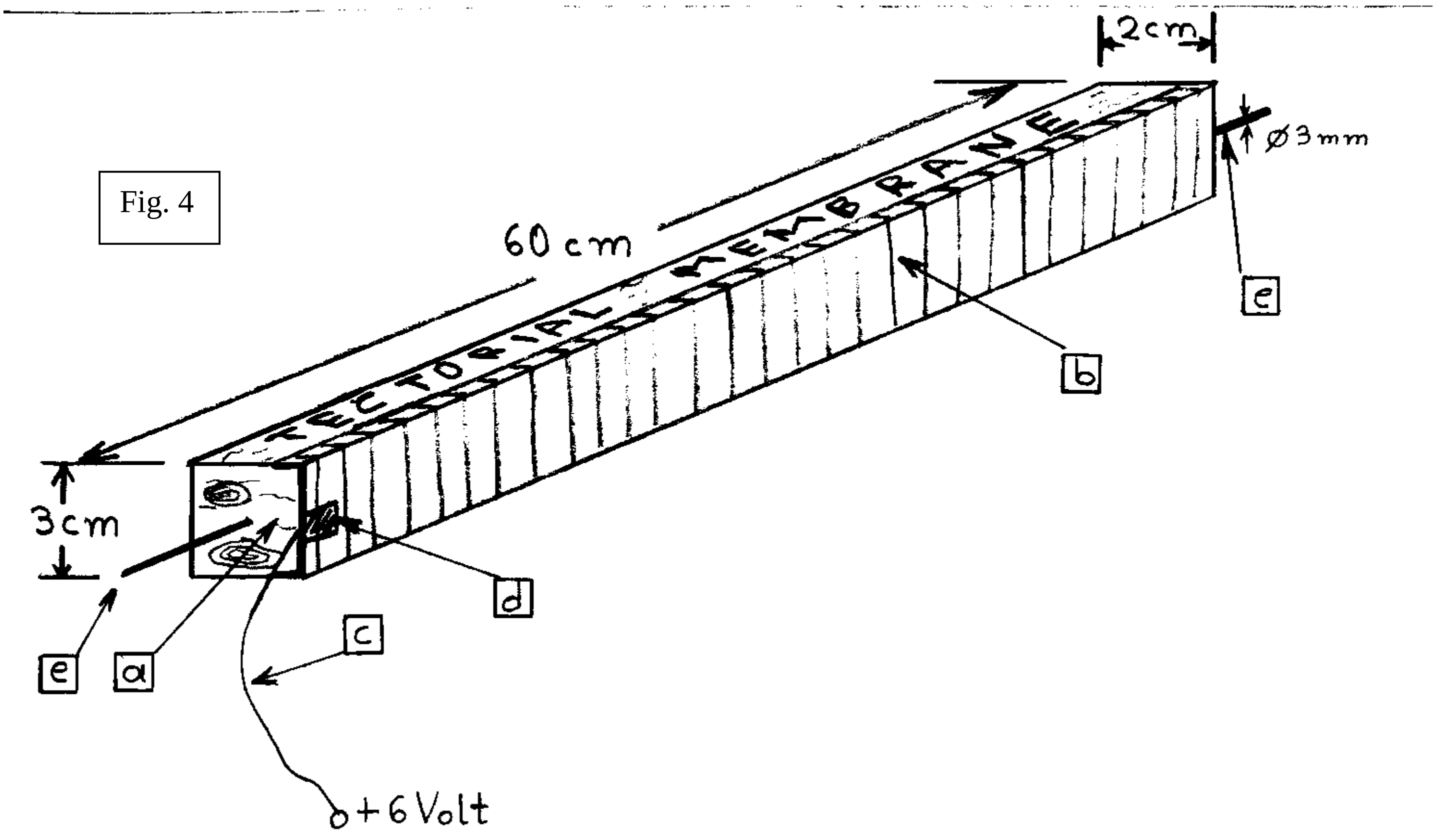
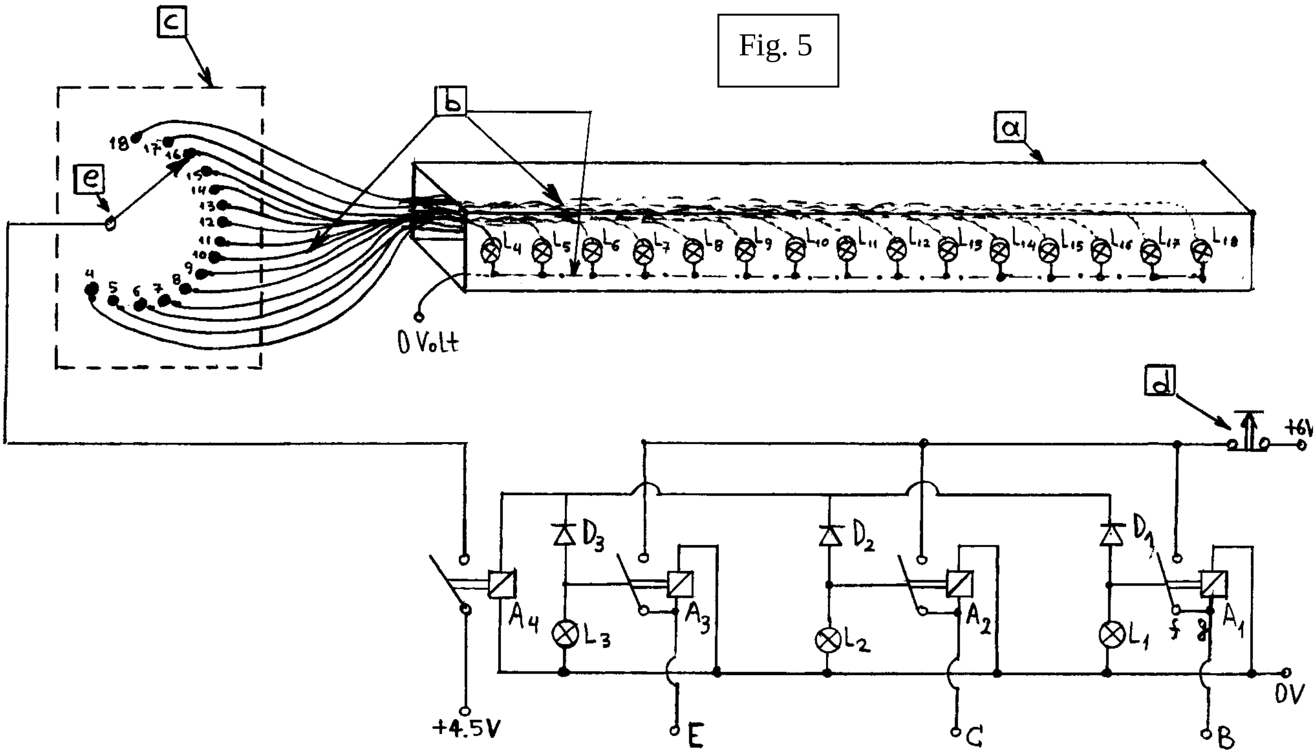


Fig. 4

a: wooden batten.
b: aluminium self – adhesive tape.
c: lead.
d: small piece of aluminium self-adhesive tape to hold lead c (so, there is an electrical connection between tape b and lead c).
e: supporting brass axles of length 8 cm each (length of 4 cm is in the wood).

5. Circuits diagrams representing the transmission of electric signals to the brain. (fig. 5)

Fig. 5



a: Plastic electric trunking conduit (dimensions 59 cm X 2 cm X 2 cm) . This conduit is part IJ in photograph 4. The 3.8Volt bulbs L_4, L_5, L_6, … , L_{18}, are fixed to one side of the conduit.
b: Leads.
c: Revolving switch (contacts 4, 5, 6, … , 18 are the same as 4, 5, 6, … , 18 in fig. 6 where the construction of this switch is shown).
d: Push- button on/off switch(see **a** in photograph 5).
e: Central screw of switch (see a, fig. 6).
A_1, A_2, A_3 : Small 6 Volt relays.
A_4 : Small 6 Volt relay.
L_1 : 3.8 Volt yellow bulb.
L_2 : 3.8 Volt green bulb.
L_3 : 3.8 Volt red bulb.
D_1, D_2, D_3 : diodes (1N 4007)
B,C,E : are the same as B, C, E in fig. 3.

Notes.
a) The function of circuits will be explained later.
b) All circuits, except a (plastic electric trunking conduit) are fixed behind part KLMN (photograph 4) which represents the brain (see fig. 8).

6. Revolving switch (from simple materials) (fig. 6)

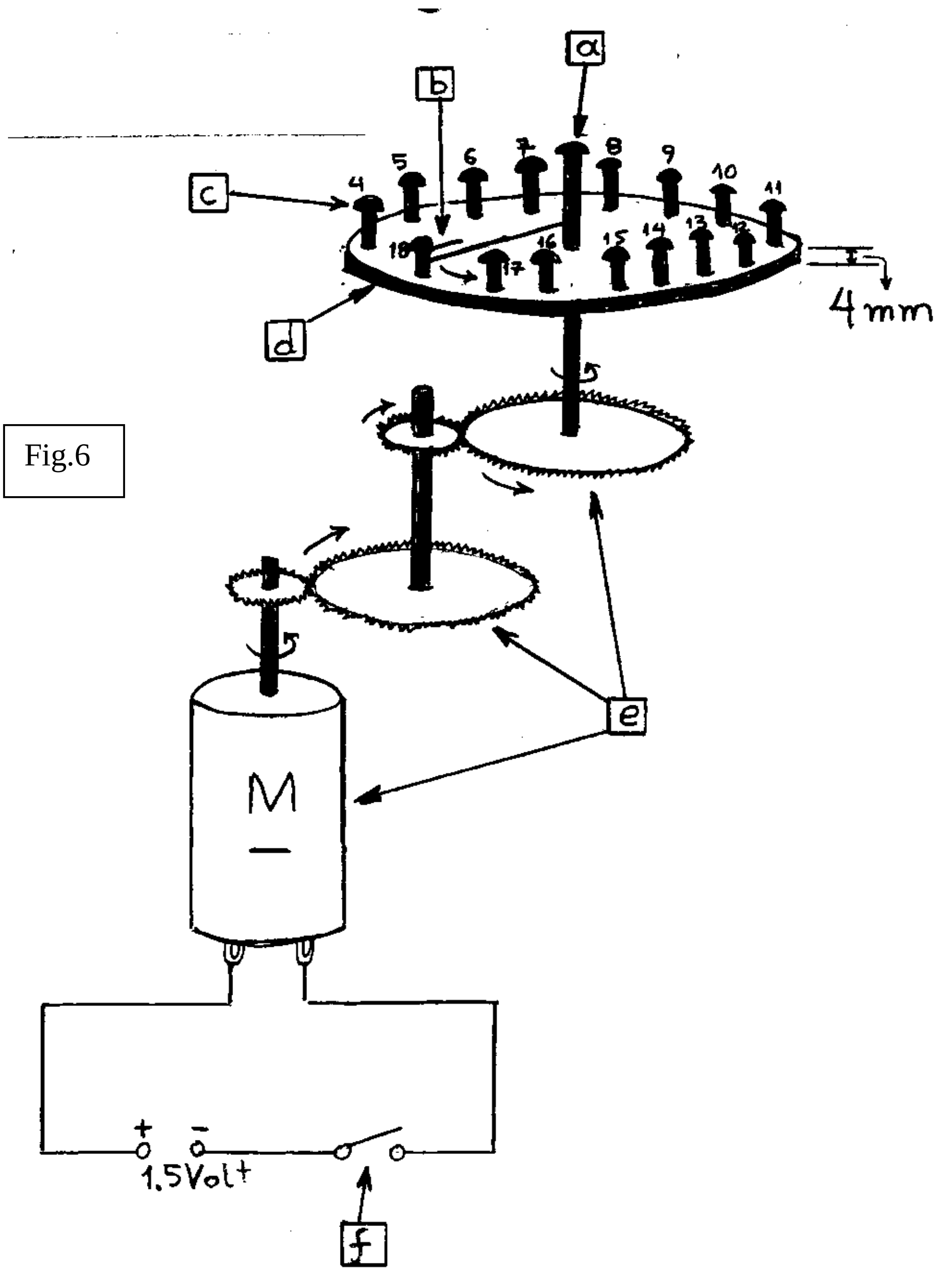


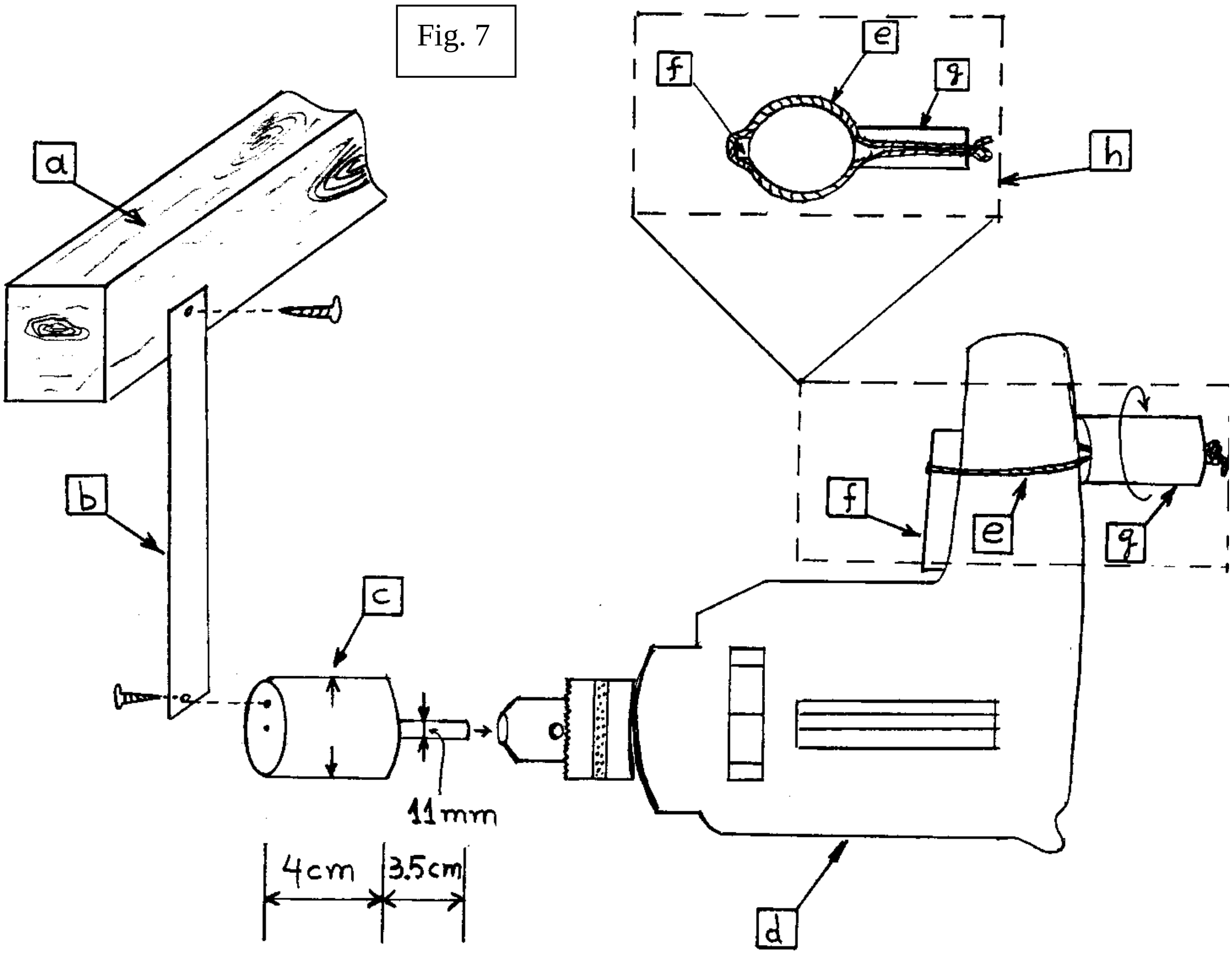
Fig.6

a: Central revolving screw.
b: Revolving contact wire (one end is soldered to the central screw and the other end comes into contact with screws 4,5,6,…18).
c: One of fifteen screws (4, 5, 6,…18) which are screwed to disk d peripherally. The leads b in fig. 5 are soldered to the tops of these fifteen screws.
d: Plexiglas disk (diameter 8 cm).
e: This is a small motor with gears taken from a children's toy. The last gear drives the central screw a
f: Simple switch.

Note
An electronic revolving switch could be used but the aim was to construct this from simple materials because it is easier to understand the function.

7. Construction of eccentric drive (OP in photograph 5) see fig. 7.

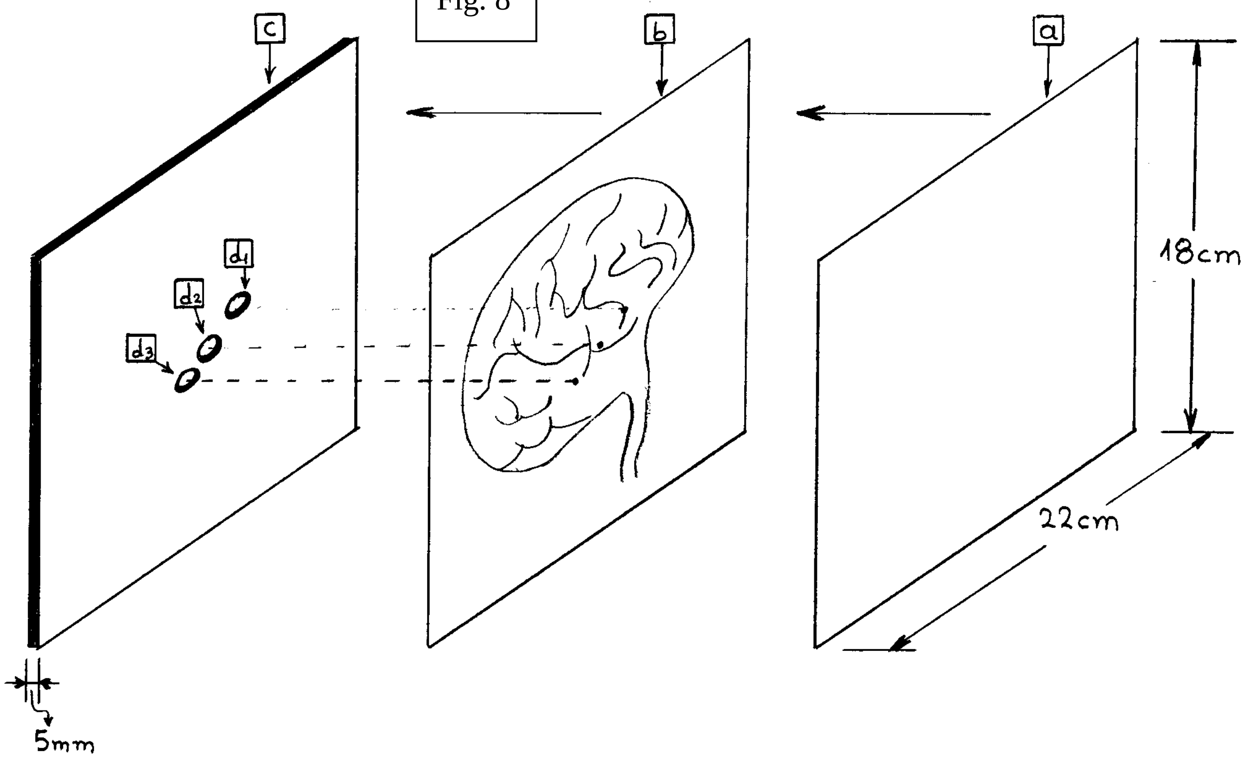
Fig. 7



a: Part of " T- piece" (see e_1 in fig.3).
b: Steel strip, dimensions 34 cm X 2 cm X 3 mm (see f in fig 3 and OP in photograph 5)
c: This cylinder is made from "Ertalon" a strong plastic material. It is rotated by the electric drill (see g in fig 3)
d: An ordinary variable speed electric drill which is fixed on the table.
e: String
f: Drill trigger.
g: Piece of plastic tube, closed at one end. String e is looped around the trigger and handle and the ends of the string are passed through the tube and tied off at the closed end. When the tube is rotated by hand, the tension in the loop increases and applies a steadily increasing pressure on the trigger. Consequently, the drill speed slowly increases and this helps to ensure that all the hoop irons resonate in succession.
h: Top view.

8. Representation of the brain (KLMN in photograph 4). See fig. 8.

Fig. 8



a: Transparent film.
b: Photocopied illustration of the brain (painted).
c: Plywood 5 mm thick (electrical circuits are mounted behind this)
d_1, d_2, d_3 : Holes (yellow bulb L_1 (fig.5) is fixed behind hole d_1 , green bulb L_2 behind d_2 and red bulb L_3 behind d_3).

Note
Colour threads a in photograph 4 represent the nerve fibres which are a connection between the hair cells and the auditory nerve IJ.

C USING THE APPARATUS.

1. The physiological construction of the human ear

Place the stapes in contact with the oval window and explain the components of the construction.

Note:

The representation of the cochlea in this construction is mechanical and consequently it cannot show the interaction between the tension applied by the stirrup bone and the fluid naturally found in the cochlea via the oval window.

Remove the cochlea so that the auditory ossicles remain free to vibrate. A low frequency generator is used to produce sound from the loudspeaker and this sound can be shown to cause the auditory ossicles to vibrate. In the range 0 to 150 Hz there are specific frequencies which will stimulate this vibration and for this construction the frequencies are 22 Hz, 45 Hz and 100Hz.

2. The operation of the basilar membrane

Motor M is started with switch *f.* fig. 6. Slowly turning plastic cylinder *g*, fig. 7, by hand, tightens string *e*. This applies pressure to the trigger of the electric drill which begins to turn. This arrangement allows the speed of the drill to be controlled with a high degree of accuracy. As the speed is increased, the first of the yellow hoop-irons strips begins to resonate (a, fig.3). As soon as the foil covered cork attached to the strip makes contact with the model of the tectorial membrane (see photograph 4), relay A_1 is activated (fig. 5) and the yellow bulb L_1 (fig 5) is turned on. (Diodes D_2 and D_3 prevent the green bulb L_2 and the red bulb L_3 from lighting.) The activation of relay A_1 energises relay A_4 and this causes bulbs L_4

– L_{18} to turn on and off one after the other because of the action of the rotary switch shown in c, fig. 5.

As the drill's revolutions increases then the remaining hoop-iron strips connected to yellow bulb begin to resonate in turn. Bulb L_1 remains illuminated because relay A_1 remains energised due to the connection between contacts *f* and *g* (fig. 5).

Just before the strips connected to the green corks begin to resonate, relay A_1 is de-activated by pressing the push-button switch (d, fig. 5 and a in photograph 5) and bulb L_1 is turned off. As soon as the first green cork makes contact with the tectorial membrane, relay A_2 (fig. 5) is activated and this turns on the green bulb L_2. The same procedure activates relay A_3 and the red bulb L_3.

It is essential to keep the drill's revolutions stable for a short time so that it can be seen that only one strip at a time is resonating.

EPILOG.

I wish good luck to those who will try to make the construction!

Ilias Kalogirou
GREECE