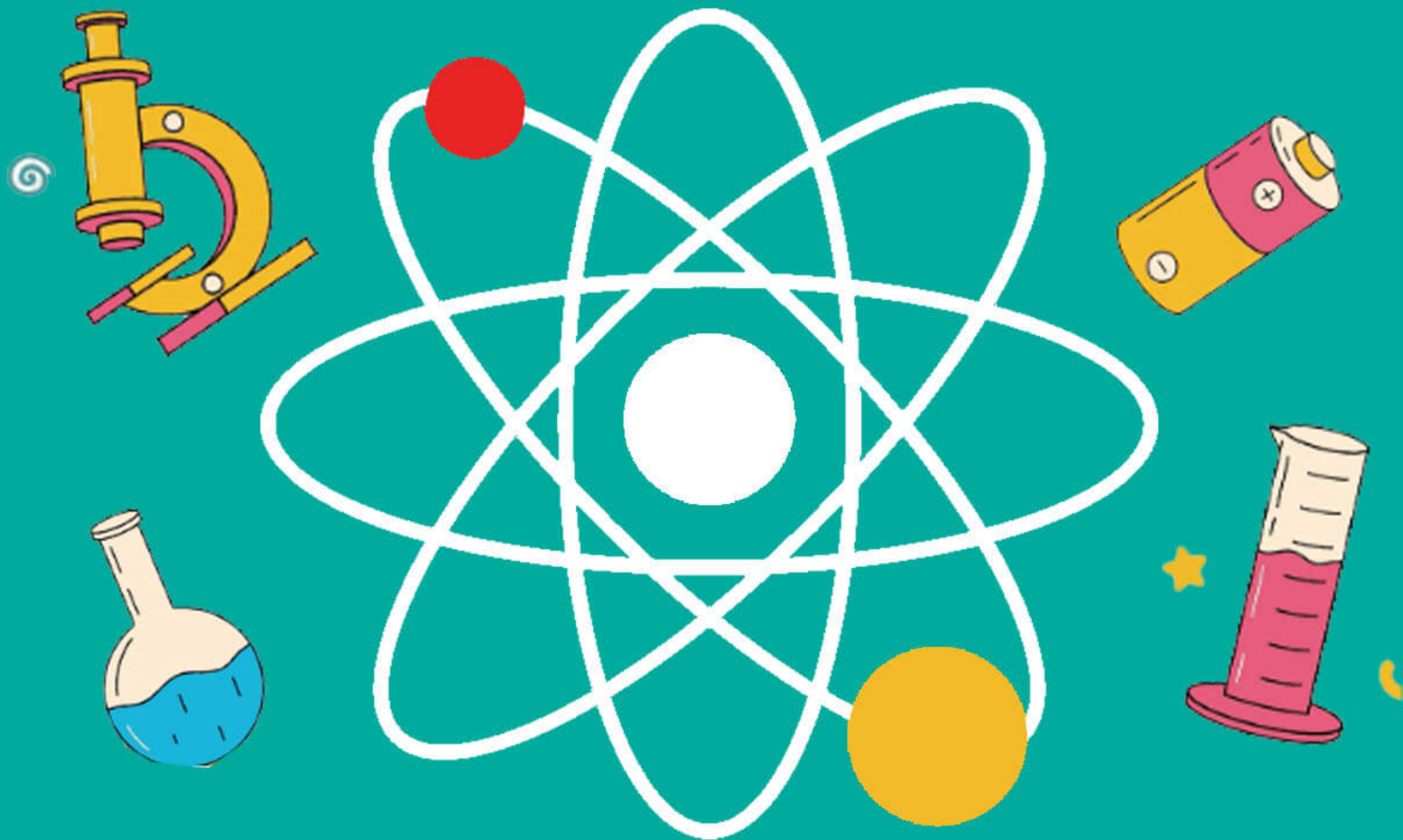
Exam Papers Practice

10.2 Physics of the Ear



AQA A Level Physics Revision Notes

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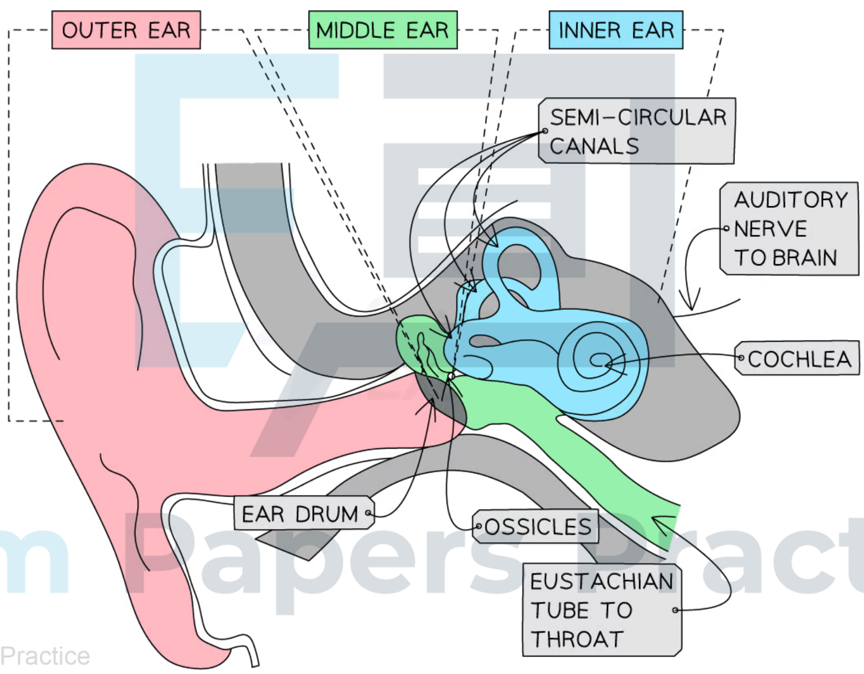
10.2.1 Structure of the Ear

Structure of the Ear

- The human ear can be divided into three main regions
  - The **outer** ear
  - The **middle** ear
  - The **inner** ear

The Outer, Middle & Inner Ear

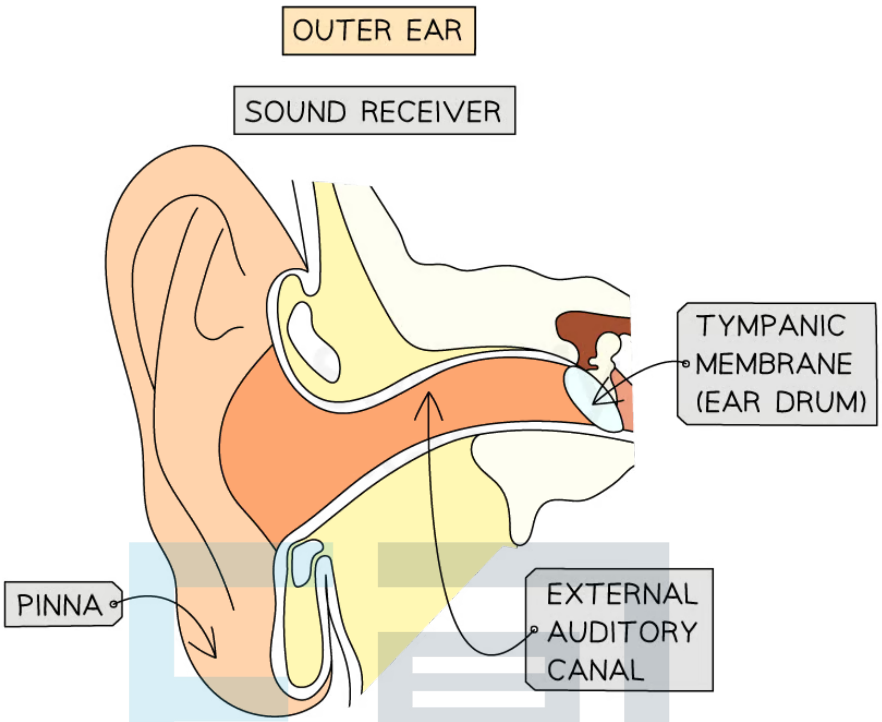
- 

Sound is received by the outer ear, amplified by the middle ear and converted to electrical impulses by the inner ear

The Outer Ear

- The purpose of the outer ear is to **receive** sound waves and relay them to the eardrum
- The main components of the outer ear are:
  - The ear flap, or **pinna**
  - The ear canal, or **external auditory canal**
  - The ear drum, or **tympanic membrane**

Structure of the Outer Ear



The outer ear comprises the pinna, the auditory canal and the tympanic membrane

Pinna

- The function of the pinna is to **reflect** sound waves into the ear canal
- This concentrates the energy onto a smaller area which increases the intensity of the waves
- As a result, it enables very quiet sounds to be detected

Auditory canal

- The function of the auditory canal is to relay sound waves to the ear drum and cause it to vibrate
- The effects of resonance on sound in the auditory canal are responsible for the range of human hearing which, on average, is 20 to 20,000 Hz

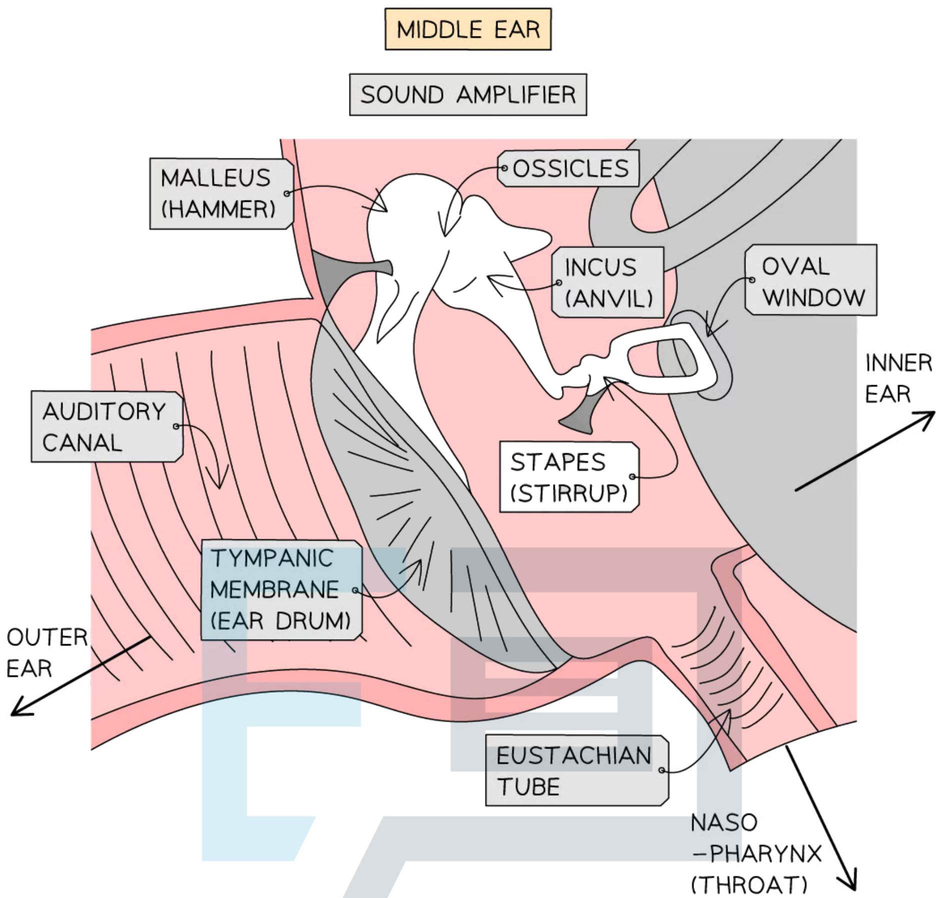
Tympanic membrane

- The function of the tympanic membrane (ear drum) is to transfer vibrations into mechanical oscillations
- It forms a boundary between the outer ear and the ossicles of the middle ear

The Middle Ear

- The purpose of the middle ear is to **amplify** vibrations on the eardrum and transmit them to the inner ear
- The main components of the middle ear are:
  - The **Eustachian tube**
  - Three small bones called **ossicles**

Structure of the Middle Ear



The middle ear comprises the Eustachian tube which connects to the throat, and the ossicles (malleus, incus and stapes) which connect the ear drum to the oval window

Eustachian tube

- The function of the Eustachian tube is to **equalise** pressure differences between air in the middle ear and outside the ear
- The Eustachian tube connects the cavity in the middle ear to the nasopharynx, or throat

Ossicles

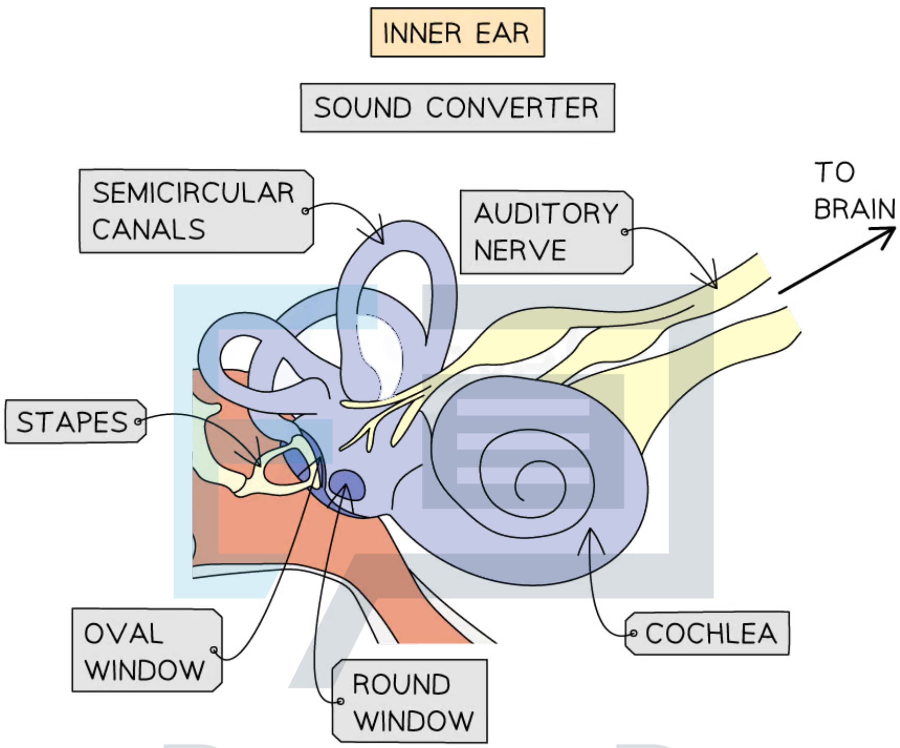
- The function of the ossicles is to transmit, and **amplify**, vibrations of the tympanic membrane to the oval window in the inner ear
- The ossicles comprise three small bones, which are named after their shapes:
  - The malleus (hammer)
  - The incus (anvil)
  - The stapes (stirrup)
- The three bones act as a system of **levers** which can achieve a multiplication of force, or **amplification**, of vibrations by about 1.5 times, or 50%
- The ossicles **tighten** under quiet conditions and **loosen** under loud conditions
- This loosening of muscle is a protective measure which prevents hearing loss

The Inner Ear

- The purpose of the inner ear is to **convert** vibrations to electrical signals to be processed by the brain

- The main components of the inner ear are:
  - The **oval** window
  - The **round** window
  - The **cochlea**
  - The **semi-circular canals**

Structure of the Inner Ear



The inner ear comprises the oval window, round window, the cochlea and the semicircular canals

Oval window

- The function of the oval window is to allow vibrations to **enter** the fluid of the cochlea
- The oval window is a thin membrane which connects the stapes bone in the middle ear to the apex (top) of the cochlea
- The amplification of sound occurs here as the oval window has a smaller area (about 20 times smaller) than the tympanic membrane

Round window

- The function of the round window is to allow the **movement** of fluid in the cochlea by relieving the pressure
- The round window is a thin membrane below the oval window
- As the stapes presses the oval window inwards, the pressure in the fluid causes the round window to be pushed outwards

Cochlea

- The function of the cochlea is to **convert** vibrations into electrical signals to be processed by the brain
- The cochlea is a helical, spiral-shaped cavity filled with fluid
- One end connects to the **oval window** and the lower end connects to the **round window**
- The cochlea contains the **basilar membrane** which is lined with rows of hair cells

- The distortion of the hair cells produces electrical impulses which travel along the **auditory nerve** to the brain

Semi-circular canals

- The function of the semi-circular canals is to **maintain balance** and detect changes in velocity
- There are three semi-circular canals, each containing fluid which detects acceleration in the three perpendicular planes

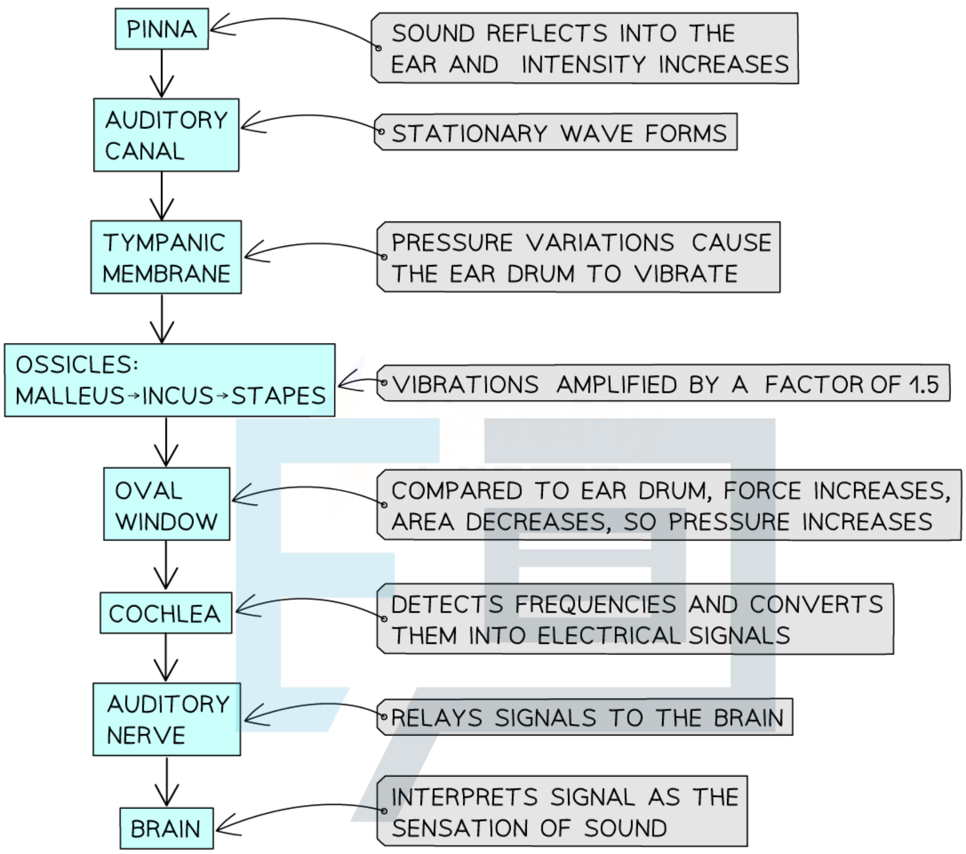
Exam Tip

Make sure you can label all the structures of the ear and succinctly summarise their functions

Transmission Processes of Sound

- The transmission of sound from the outer ear to the brain is shown below:

Transmission of Sound in the Ear



The process by which sound produces vibrations in the outer ear, middle ear and inner ear before reaching the brain

Transmission of Sound in the Outer Ear

- Sound waves are reflected into the **auditory canal** by the **pinna**
- The intensity of the sound increases as energy is concentrated onto a smaller area
- The sound wave travels down the auditory canal towards the **tympanic membrane** (ear drum)
  - The pressure variations created by the longitudinal sound wave exert a force on the ear drum, causing it to vibrate
  - The vibration pattern of the sound waves creates the same pattern of vibration in the ear drum

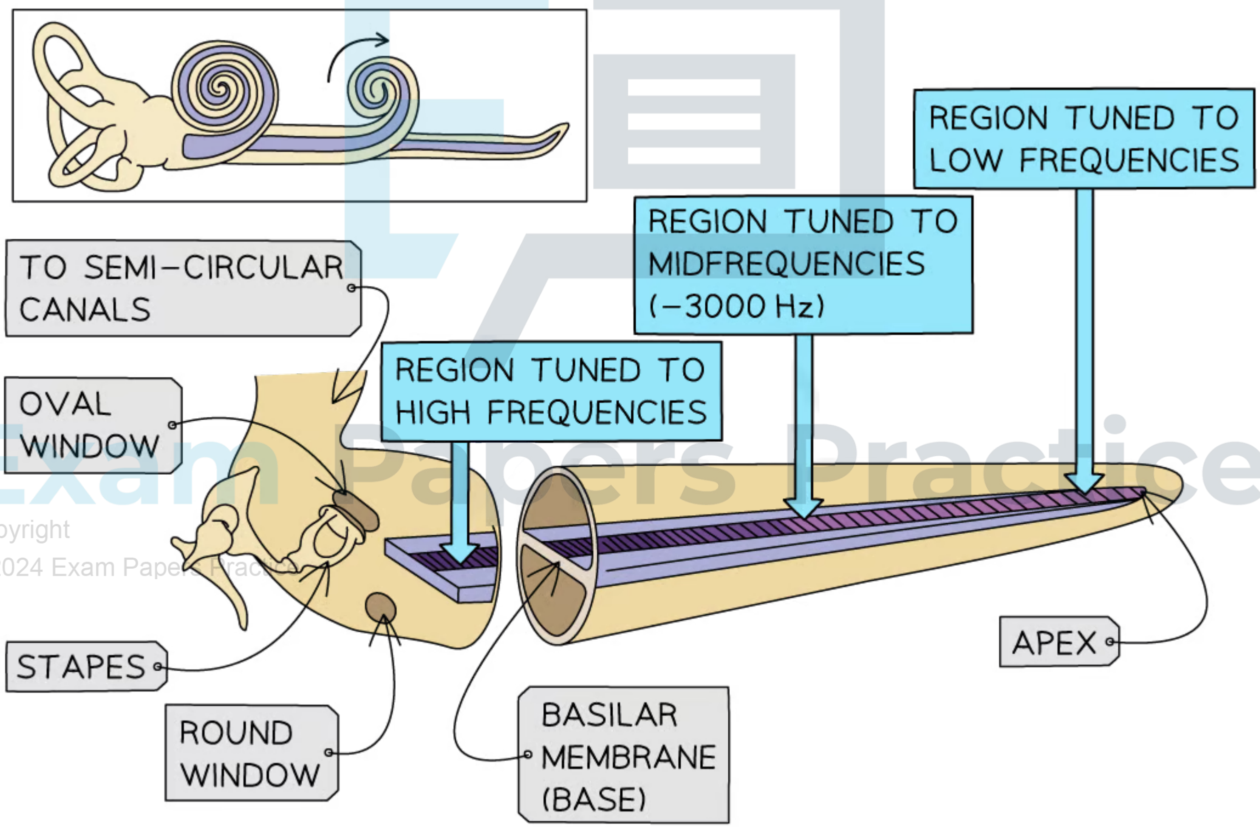
Transmission of Sound in the Middle Ear

- The vibration of the ear drum is transferred to the **ossicles**
  - The **malleus** (hammer) transfers the vibration to the **incus** (anvil) and **stapes** (stirrup)
- The action of the ossicles **amplifies** the vibrations and **reduces** any energy which is reflected back
- The stapes bone transfers the vibrations to the **oval window**
  - The oval window has an area which is only 1/15 of that of the eardrum, and a force of 1.5 times greater, hence there is an increase in the **pressure** by about 20 times

Transmission of Sound in the Inner Ear

- The oval window transfers the vibrations to the **fluid** in the cochlea in the inner ear
  - As the pressure pushes the oval window inwards, the round window bulges out to compensate for the pressure change
- As vibrations are transmitted along the cochlea, movement in the **basilar membrane** causes small hairs to bend backwards and forwards
- Different regions of the basilar membrane have different **natural frequencies**
- This means different frequencies of sound resonate in different parts of the cochlea
  - High frequencies are detected at the **base**
  - Lower frequencies are detected at the **apex**
- The tiny hairs produce **electrical impulses** which correspond to the different frequencies
- These impulses travel along neurones in the **auditory nerve** to the brain, which is interpreted as the sensation of sound

An Uncoiled View of the Cochlea



This uncoiled view of the cochlea shows how the ear detects different frequencies

Worked example

The oval window has an area which is about 15 times less than the area of the ear drum.

The force exerted on the oval window is about 1.5 times the force exerted on the ear drum.

Show that the pressure on the oval window is over 20 times greater than the pressure on the ear drum.

Answer:

Step 1: List the known quantities:

- Area: $A_{oval} = \frac{A_{eardrum}}{15}$
- Force: $F_{oval} = 1.5\ F_{eardrum}$

Step 2: Write down the relationship between force, pressure and area:

pressure: $P = \frac{F}{A}$

Step 3: Determine the ratio of pressure on the oval window to the ear drum:

$$\frac{P_{oval}}{P_{eardrum}} = \frac{F_{oval}}{A_{oval}} \times \frac{A_{eardrum}}{F_{eardrum}}$$

$$\frac{P_{oval}}{P_{eardrum}} = \frac{1.5\ F_{eardrum}}{\frac{A_{eardrum}}{15}} \times \frac{A_{eardrum}}{F_{eardrum}} = 1.5 \times 15$$

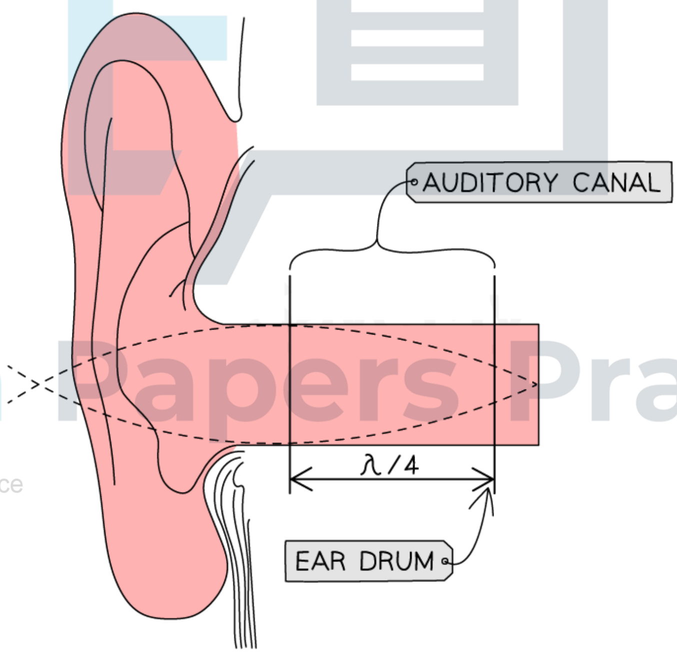
$$\frac{P_{oval}}{P_{eardrum}} = 22.5 \approx 20$$

10.2.2 The Decibel Scale

Relative Intensity Levels of Sound

- When the sound waves enter the auditory canal, a **stationary wave** is set up
  - This can be modelled as a tube with an antinode forming at the open end and a node forming at the closed end
- As a result, the auditory canal acts as a closed tube resonator which enhances the **sensitivity** of sounds in specific ranges
  - In the case of human hearing, this is what enables us to hear sounds in the range of 20 Hz to 20,000 Hz
  - The highest sensitivity region is around 2 to 5 kHz, which corresponds to frequencies of speech

Resonance in the Auditory Canal

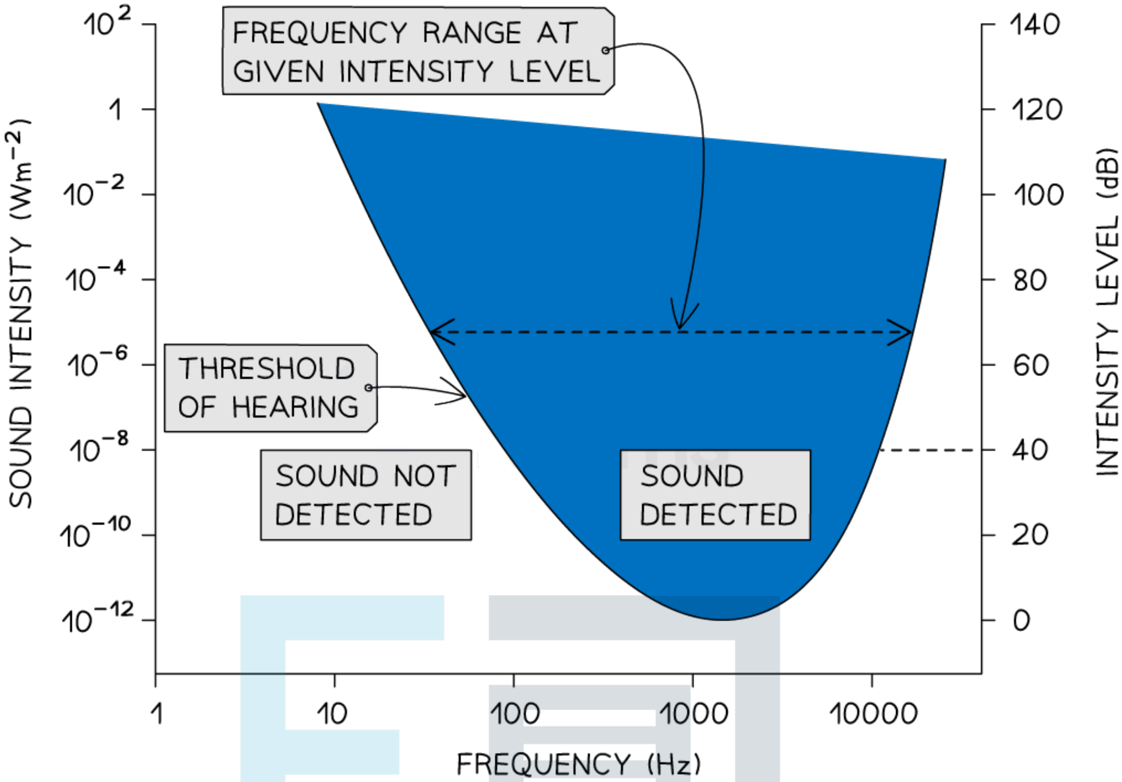


The auditory canal works as a closed tube resonator which is sensitive to specific ranges of frequencies

The Decibel Scale

- The ear's ability to detect small changes in sound intensity is referred to as its **sensitivity**
  - This is measured in **decibels** (dB)
- The **sensitivity** of human hearing depends on the **frequency** of the sound
- The graph of sound intensity and frequency shows that the ear is most sensitive to sounds with a frequency of about **3000 Hz**

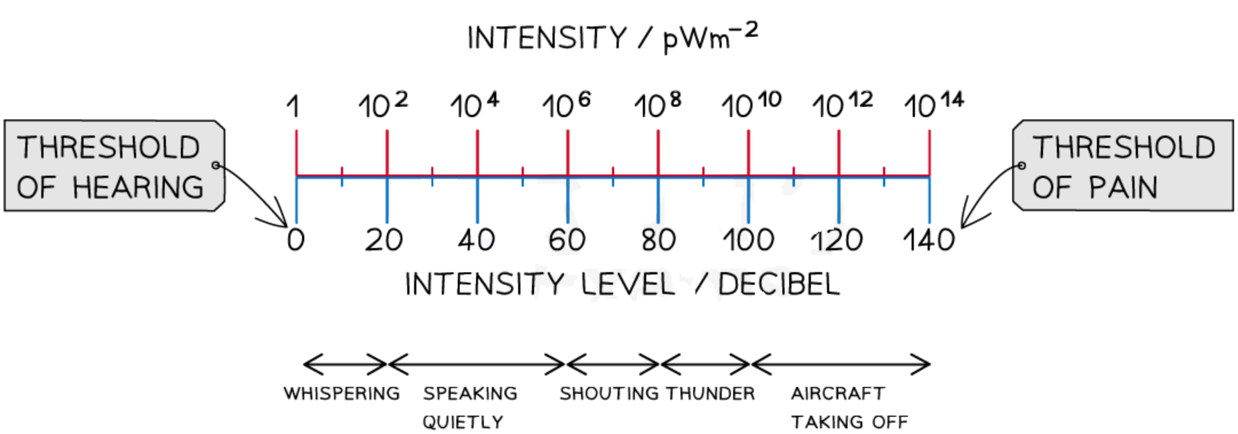
The Relationship between Sound Intensity and Frequency



The human ear is most sensitive to sounds with a frequency of around 3000 Hz

- For frequencies much greater, or lower than 3000 Hz, the intensity of sound must be several orders of magnitude higher to be detected
  - This large range of intensities shows that the response of the ear is logarithmic
- The **decibel (dB) scale** is also logarithmic
  - Hence, the decibel scale is a useful way of measuring the response of the human ear to changes in sound intensity

The Decibel Scale



The decibel scale is used to represent the large range of intensities that the ear can detect on a logarithmic scale

Worked example

Give **two** reasons why logarithmic scales are used to measure the loudness of a sound.

Answer:

- The ear can detect sounds over a very large range of intensities, across many orders of magnitude
- This means the ear's perception of loudness is logarithmic
- Therefore, a logarithmic scale is a useful way to plot or analyse such a large range of numbers
- For example, on the graph above:
  - The range of frequency of human hearing is ~20 to 20 000 Hz
  - So, frequency values are plotted on the axes in increments of 10 (1, 10, 100, 1000, etc)
  - In this range of frequencies, intensity values range from 10^{-12} to 10^{2} W m^{-2}
  - So, intensity value are plotted on the axes in increments of 100 (10^{-12}, 10^{-10}, 10^{-8}, 10^{-6}, etc)

Loudness & Decibels

- Intensity of a sound wave is defined as:

The amount of sound energy that passes a point per second per unit area

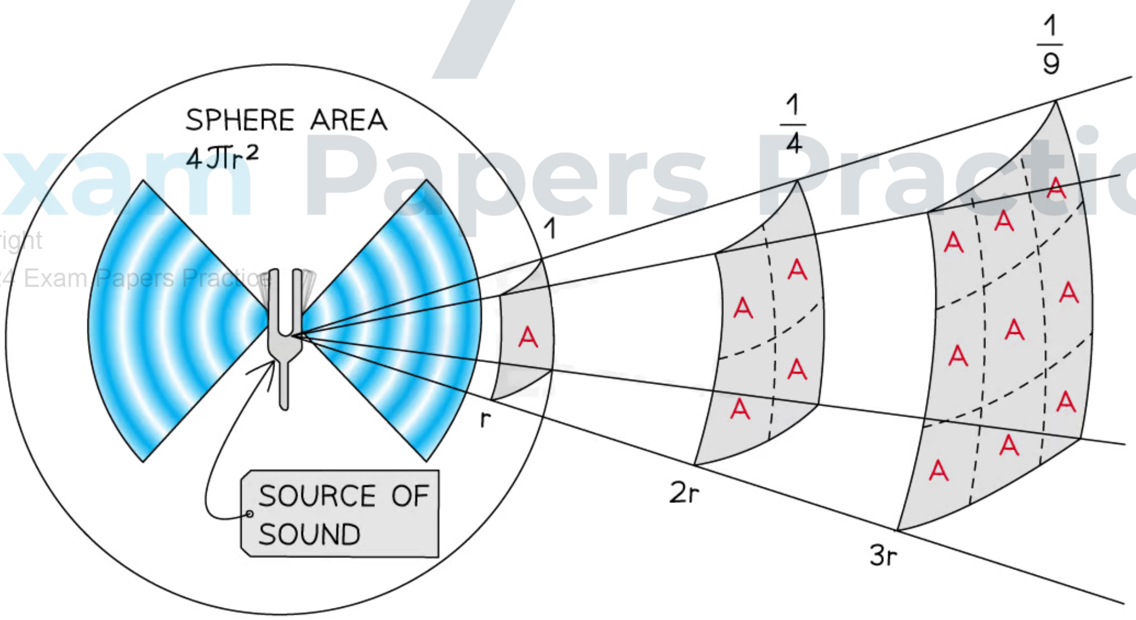
- Intensity can be described by the equation:

$$I = \frac{P}{A}$$

- Where
  - I = intensity of sound wave (W m^{-2})
  - P = power, or energy transferred per second (W)
  - A = area through which sound waves pass (m^2)
- For a sound wave that spreads out uniformly in all directions, it can be assumed to propagate as a **spherical** shell
  - The surface area of a sphere is $4\pi r^2$
  - The radius r of this sphere is equal to the distance between the source of the sound and the receiver
- This means the intensity of the sound spreads out according to an inverse square law

$$I = \frac{P}{4\pi r^2}$$

Inverse Square Law of Sound Intensity



When the source of the sound is twice as far away, it has spread over four times the area, hence the intensity is four times smaller

- The human ear can detect and respond to a very large range of intensities
- The response of the ear to changes in sound intensity, or the **perceived change in loudness**, is directly proportional to the logarithm of the percentage change in intensity

$$\text{perceived change in loudness} \propto \log\left(\frac{I_2}{I_1}\right)$$

- Where
  - I_1 = initial intensity of sound wave (W m^{-2})
  - I_2 = final intensity of sound wave (W m^{-2})
- This is known as the **logarithmic response** of sound intensity
  - This means when the intensity of a sound doubles, and doubles again the loudness increases in fixed steps (for a given frequency)
  - For example, an increase in sound intensity from 1×10^{-12} W m^{-2} to 2×10^{-12} W m^{-2} is perceived to be the same change in loudness as 1 W m^{-2} to 2 W m^{-2}
- The threshold of hearing I_0 is defined as

The lowest intensity that a normal human ear can detect at a frequency of 1 kHz

- This is equal to about 1×10^{-12} W m^{-2}
- The intensity level of a sound can be defined as

$$\text{intensity level} = 10 \log\left(\frac{I}{I_0}\right)$$

- Where:
  - Intensity level is measured in **decibels (dB)**
  - I = intensity of the sound wave (W m^{-2})
  - I_0 = threshold of hearing intensity = 1×10^{-12} W m^{-2}
- The threshold of hearing is assigned a sound level of 0 decibels, or 0 dB
  - An intensity level of 10 dB is 10 times louder than I_0, or 1×10^{-11} W m^{-2}
  - An intensity level of 20 dB is 100 times louder than I_0, or 1×10^{-10} W m^{-2}
  - An intensity level of 30 dB is 1000 times louder than I_0, or 1×10^{-9} W m^{-2}

Worked example

Person A hears a sound of intensity level 95 dB. Person B hears the same sound at an intensity level of 82 dB whilst standing 20 m away from the source of the sound.

Calculate how far away person A is from the source of the sound.

Answer:

Step 1: Convert the intensity levels in dB into intensities

$$\text{intensity level} = 10 \log\left(\frac{I}{I_0}\right)$$

- Intensity level of person A = $10 \log\left(\frac{I_A}{I_0}\right)$ = 95 dB

$$\log\left(\frac{I_A}{I_0}\right) = \frac{95}{10} = 9.5$$

- Take logs of both sides:

$$\frac{I_A}{I_0} = 10^{9.5} \Rightarrow I_A = I_0 \times 10^{9.5}$$

- Intensity level of person B = $10 \log\left(\frac{I_B}{I_0}\right)$ = 82 dB

$$\log\left(\frac{I_B}{I_0}\right) = \frac{82}{10} = 8.2$$

- Take logs of both sides:

$$\frac{I_B}{I_0} = 10^{8.2} \Rightarrow I_B = I_0 \times 10^{8.2}$$

Step 2: Use the inverse square law of intensity to find the ratio of I_A and I_B

- Intensity of a sound wave:

$$I = \frac{P}{A} = \frac{P}{4\pi r^2}$$

- Since the source of the sound is the same, the value of power *P* is the same, so $I \propto \frac{1}{r^2}$

$$\frac{I_A}{I_B} = \left(\frac{r_B}{r_A}\right)^2$$

Step 3: Rearrange and substitute values to find r_A

$$\frac{r_B}{r_A} = \sqrt{\frac{I_A}{I_B}}$$

$$r_A = \frac{r_B}{\sqrt{\frac{I_A}{I_B}}} \Rightarrow r_A = r_B\sqrt{\frac{I_B}{I_A}}$$

$$r_A = 20 \times \sqrt{\frac{10^{8.2}}{10^{9.5}}} = 4.5 \text{ m}$$

- Hence, person A is standing 4.5 m from the source of the sound

Worked example

On the ground near an airport, the intensity level of an aircraft taking off is measured to be 120 dB.

Determine the intensity level, in dB, due to two aircraft taking off at the same time.

Threshold of hearing, $I_0 = 1.0 \times 10^{-12}$ W m^{-2}

Answer:

Step 1: Convert the intensity level in dB into intensity

$$\text{intensity level (dB)} = 10 \log\left(\frac{I}{I_0}\right)$$

- Intensity level due to each aircraft = 120 dB

$$10\log\left(\frac{I}{I_0}\right) = 120 \quad \Rightarrow \quad \log\left(\frac{I}{I_0}\right) = 12$$

- Take logs of both sides:

$$\frac{I}{I_0} = 10^{12} \quad \Rightarrow \quad I = 10^{12} I_0$$

- **Note:** This is equivalent to $I = (10^{12}) \times (1.0 \times 10^{-12}) = 1.0 \text{ W m}^{-2}$, but it is simpler to keep in terms of I_0

Step 2: Add the intensities together to obtain the total intensity

- Intensity due to both aircraft:

$$I = 10^{12} I_0 + 10^{12} I_0 = 2 \times 10^{12} I_0$$

Step 3: Convert the intensity back into dB using the intensity level equation

$$\text{intensity level (dB)} = 10\log\left(\frac{2 \times 10^{12} I_0}{I_0}\right) = 10\log(2 \times 10^{12})$$

intensity level due to both aircraft = **123 dB**

Exam Tip

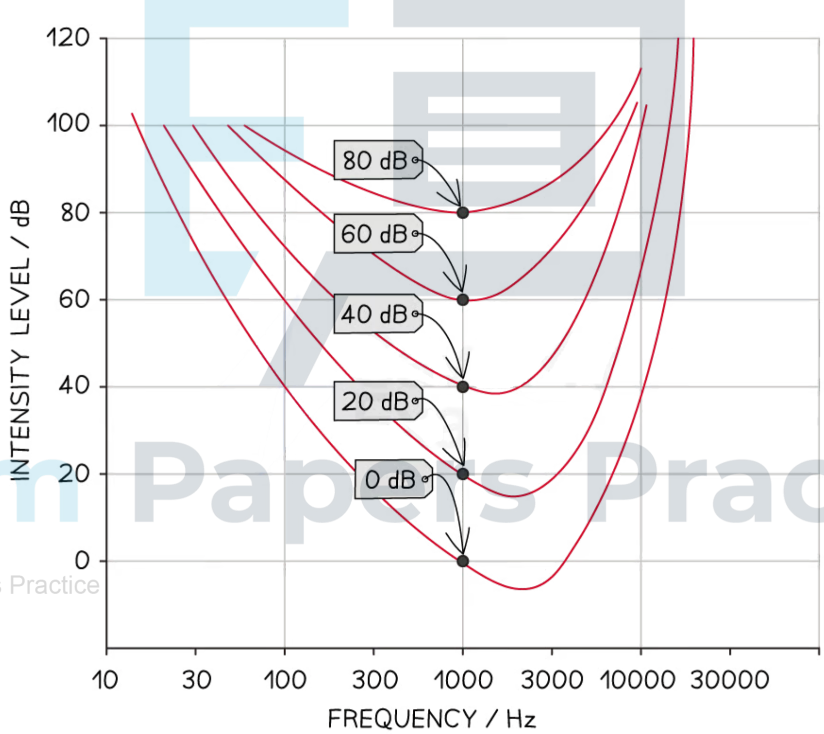
For **two or more** sounds, intensity levels in decibels cannot be added together to obtain a total intensity level, as this is not how logarithmic scales work. Remember to convert the values in decibels into intensities in W m^{-2}, then you can add them together and convert back into decibels to obtain the intensity level of the combined sound waves.

10.2.3 Equal Loudness Curves

Equal Loudness Curves

- The normal human ear can detect sounds of frequencies from about 20 Hz to 20 000 Hz
- Different people may **perceive sound differently** due to a range of factors
  - For example, hearing loss can occur due to ageing or exposure to excessive noise
- Equal loudness curves can be produced to gain an understanding of an individual's hearing abilities
  - All sounds on a given curve are perceived as **equally loud**
- An equal loudness curve is a plot of **intensity level**, in dB, against **frequency**, in Hz
  - Both axes use a logarithmic scale to match the large range of intensities and frequencies the human ear can detect

Equal Loudness Curve for a Normal Ear



Equal loudness curves for a normal ear show the sound intensity level required to produce the same sensation of loudness at different frequencies

- The loudness of a sound, for a given person, can be measured by comparing it with a standard source of sound at 1 kHz
- The process for generating an equal loudness curve is as follows:
  1. A **reference signal** is played through a pair of earphones - this is a sound of frequency 1 kHz at a fixed intensity level (volume)
  2. A sound of a **different frequency** is played through the earphones

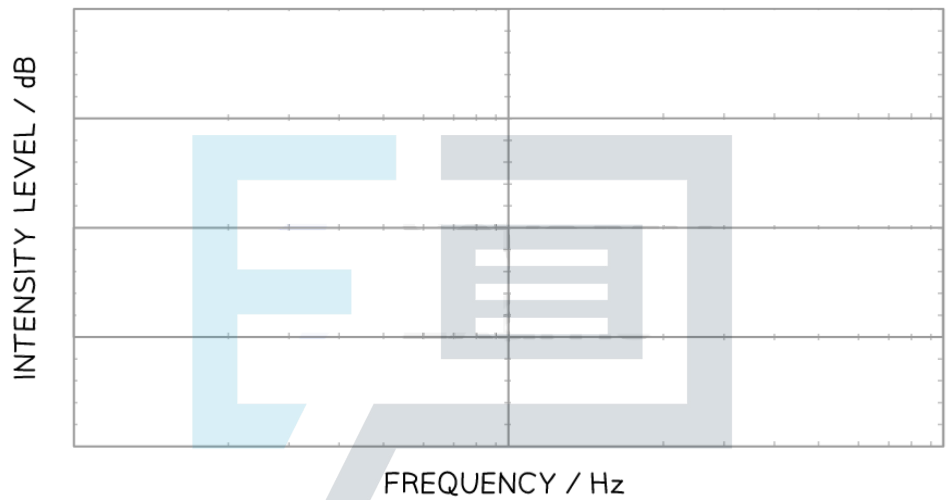
3. The intensity level (volume) of the sound is **adjusted** until both sounds seem to have the same loudness - the intensity level of this point is recorded

4. The process is repeated at different frequencies, then a curve can be plotted on a graph of intensity level against frequency - this is the **equal loudness curve**

Worked example

On the axes below, sketch an equal loudness curve showing the normal response of a healthy ear.

Annotate the frequency axis with an appropriate scale.



Answer:

Step 1: Recall the frequency range of human hearing

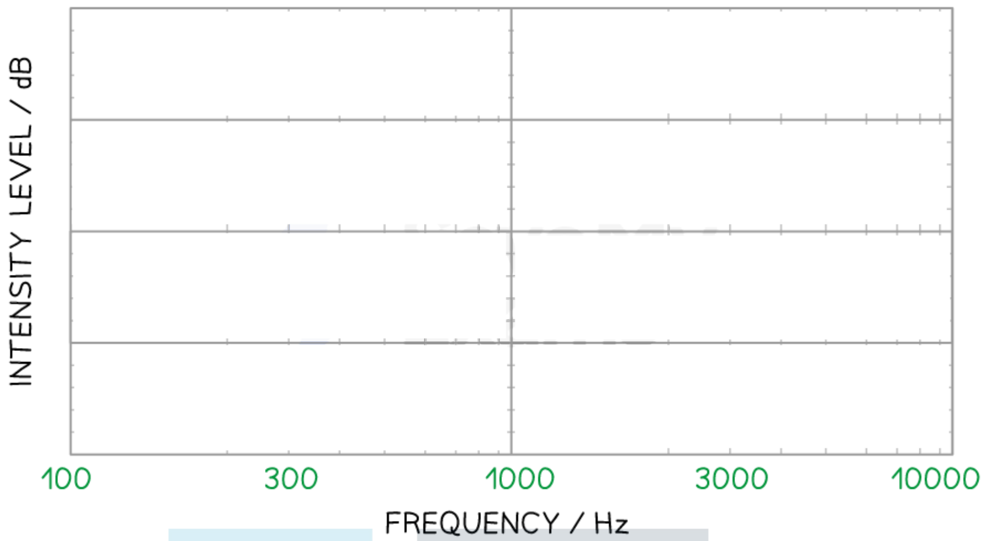
- For a normal ear, the range of human hearing is 20 to 20,000 Hz

Step 2: Recall how to plot a logarithmic scale

- On a logarithmic scale, each large division on the scale represents an increase by the base of the log (usually 10) to a power that increases linearly (i.e. 10^1, 10^2, 10^3)
- Then for each small division, instead of progressing linearly (e.g. 0, 1, 2, 3, 4...), a logarithmic scale progresses nonlinearly, but still in equal increments (e.g. 10, 20, 30, 40...)

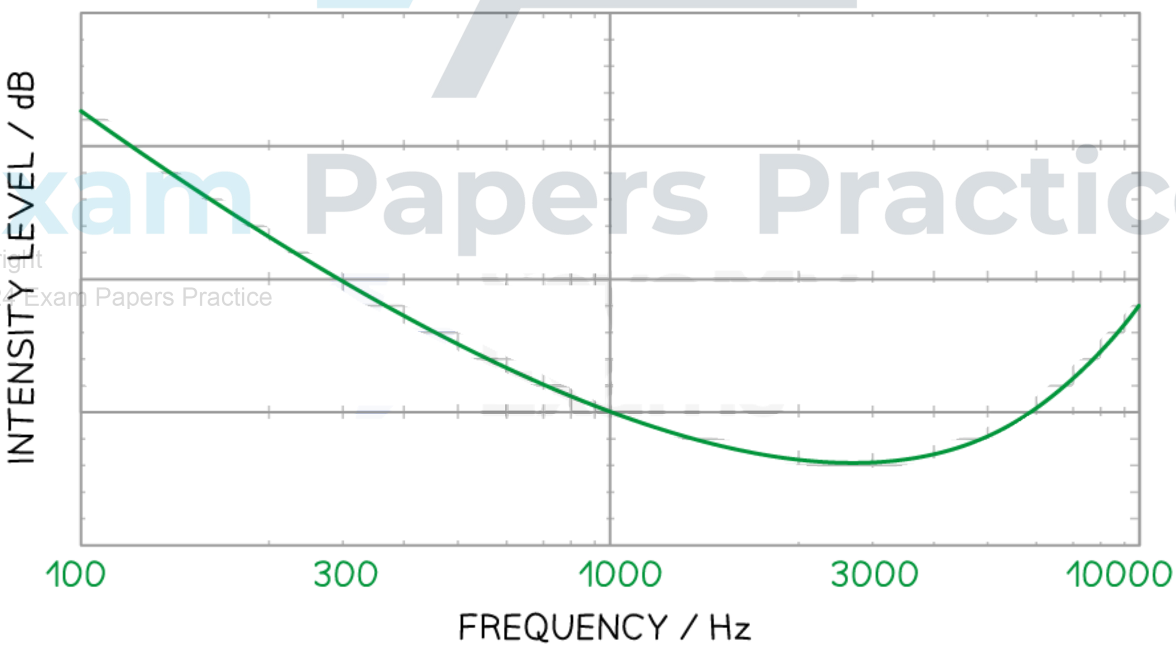
Step 3: Label the frequency axis with a logarithmic scale

- There are 3 large divisions on the axes provided, so we should plot the frequencies between 100, 1000 and 10 000 Hz, as this range is where the ear is most sensitive
  - 10, 100 and 1000 Hz would be **too low** of a range
  - 1000, 10 000 and 100 000 Hz would be **too large** of a range
- Between the large divisions, there are 9 small divisions - there is no 'zero' on a logarithmic scale, so each small division represents increments of 100 and 1000 respectively



- The scale should start at 100 Hz, then 1000 Hz at the midpoint, and end at 10 000 Hz
- Between 100 Hz and 1000 Hz, each division on the scale represents 100 Hz
- Between 1000 Hz and 10 000 Hz, each division on the scale represents 1000 Hz
- Therefore, the locations of 300 Hz and 3000 Hz are two divisions from 100 Hz and 1000 Hz respectively

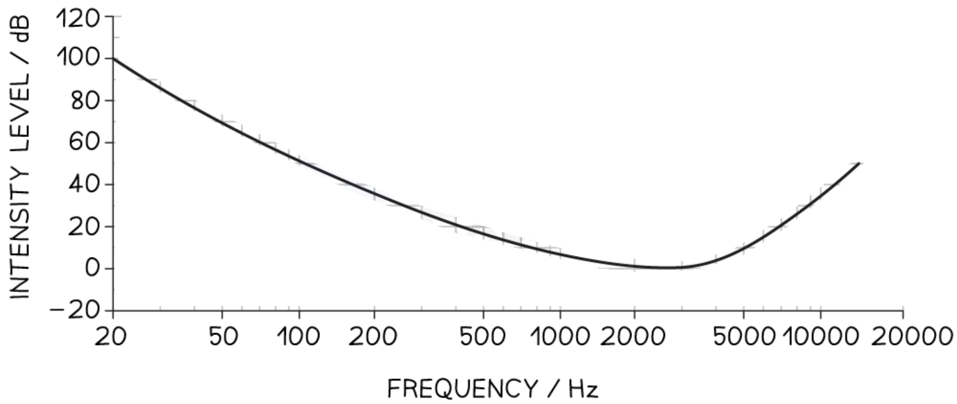
Step 4: Draw a U-shaped curve with the lowest point at 3000 Hz



- The equal loudness curve for a normal ear has a U-shape
- The frequency a normal ear is most sensitive to is about **3000 Hz**
- Therefore, this corresponds to the quietest sound or lowest intensity level on the decibel scale

Worked example

The diagram shows the equal loudness curve obtained when a patient has a hearing test at a level above the threshold of hearing.



(a) Explain how the equal loudness curve was obtained.

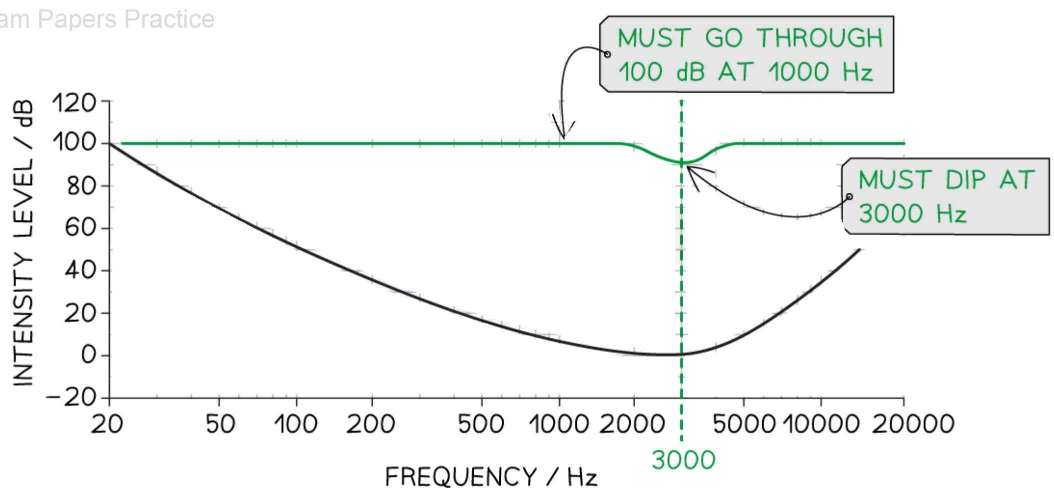
(b) On the diagram draw an equal loudness curve which passes through 100 dB at a frequency of 1 kHz.

Answer:

(a) Hearing test to generate the equal loudness curve:

- The patient listens to a reference sound at 1 kHz and intensity level 10 dB
- Then they listen to a sound at a different frequency and loudness
- They switch between the sound at 1 kHz and the sound at the new frequency and the loudness is adjusted until the same loudness is perceived - the value of loudness is recorded
- The process is repeated for frequencies between 20 Hz and 20 kHz

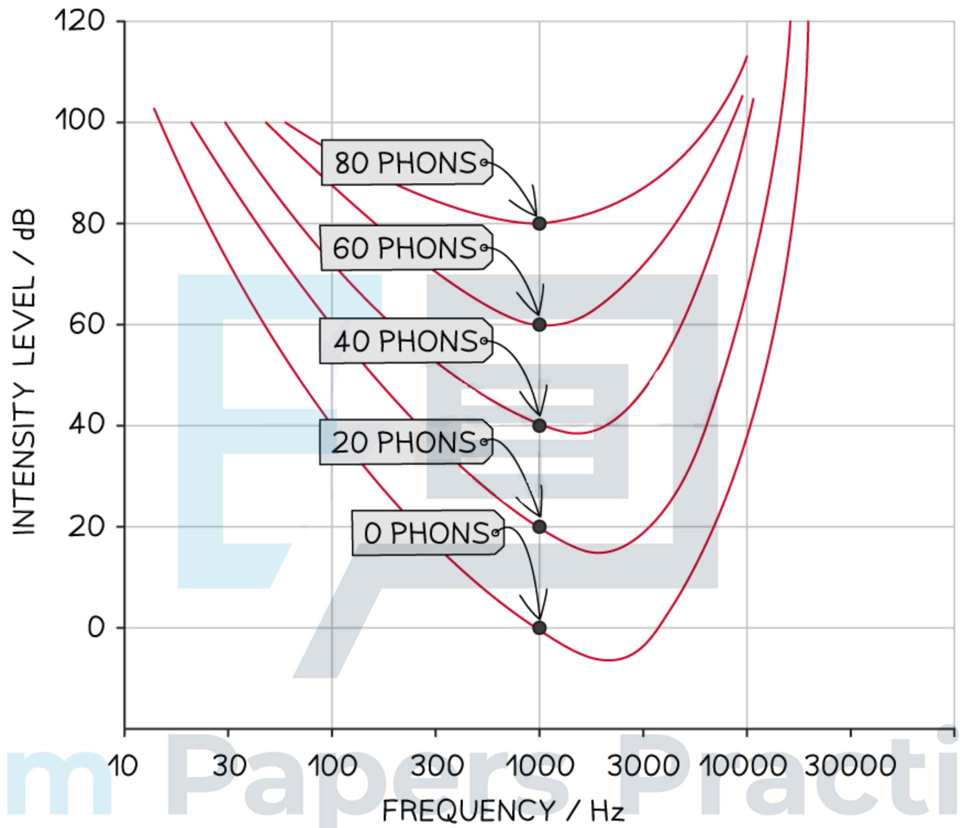
(b) Equal loudness curve for 100 dB at 1000 Hz:



- The general shape should be flatter and must pass through point 100 dB at 1000 Hz
- Both curves are most sensitive at about 3000 Hz, so they both have a minimum intensity level here

Exam Tip

An understanding of the unit 'phon' is not required in this specification but you may come across it in your revision of equal loudness curves, so it is included here to aid your understanding

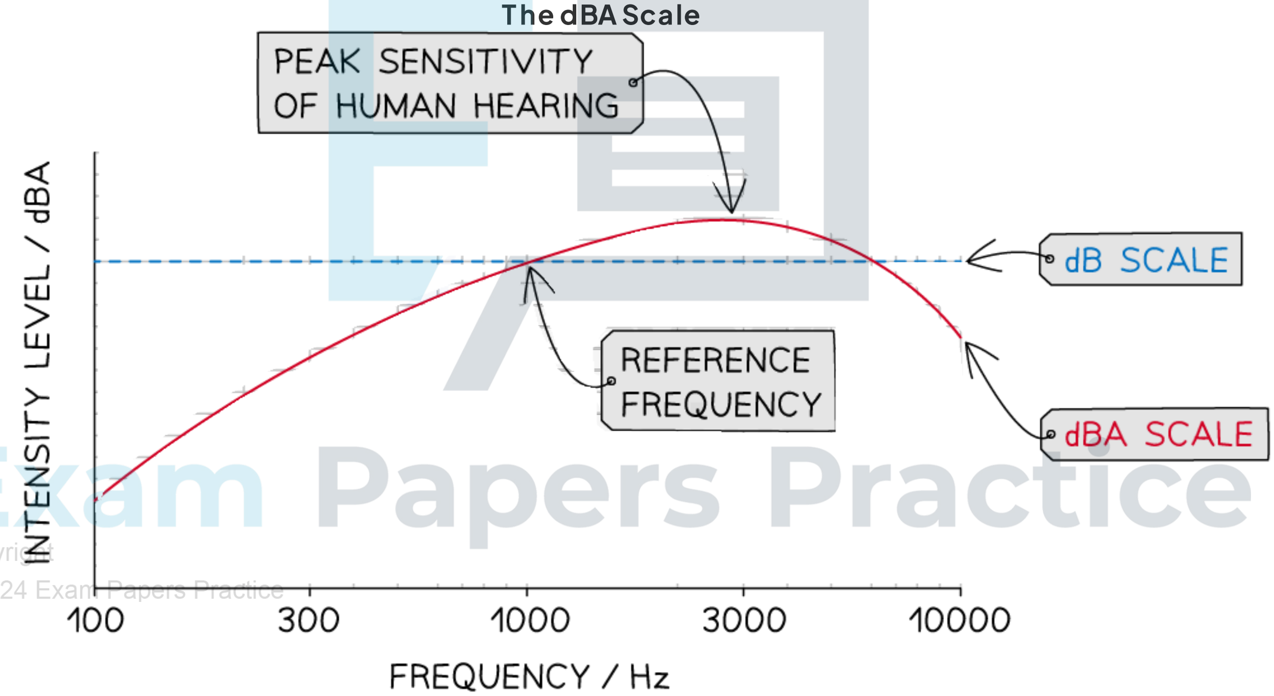


The loudness of a sound in phons is defined as the intensity level in decibels of a sound at 1000 Hz that has the same loudness as the sound, i.e. a 40 dB sound at 1000 Hz has a loudness of 40 phons. From the same curve, a 100 dB sound at 10 000 Hz also has a loudness of 40 phons.

Decibel Scales

- Sound-level meters are usually calibrated on an **adjusted decibel scale**, or the **dBA scale**
- The dBA scale gives relative measurements which take into account the ear's response to different frequencies
  - For example, the human ear is particularly sensitive to frequencies around 3 kHz and less sensitive to frequencies higher and lower than 3 kHz
- This means that for the frequency response calibrated on the dBA scale:
  - Sounds of the same intensity level (in dB) have the **same loudness** on the dBA scale - the dB output is a **flat** line
  - At **1 kHz**, the dB response and dBA response are set to be identical
  - At frequencies other than 1 kHz, the dBA response is a curve which reaches a **maximum** value around 3 kHz

The dBA Scale



The red curve shows the dBA response which simulates the response of the ear at different frequencies. The blue dotted line shows the dB response which gives an equal response across all frequencies

- At a frequency of 1 kHz (the **reference frequency**):
  - Both scales have the **same** intensity level
- At frequencies **above 1 kHz**:
  - There is an increase up to a maximum of 3 kHz (the **peak sensitivity of human hearing**)
  - Then, there is a steady decrease to simulate the ear's decreased sensitivity to **higher** frequencies
- At frequencies **below 1 kHz**:
  - There is a steady decrease to simulate the ear's decreased sensitivity to **lower** frequencies

Worked example

A sound source of constant output power is used to generate a sound which is measured using a sound meter. When set to the dB scale, the sound meter displayed 80 dB as the reading when the frequency of the sound was 1 kHz.

State and explain:

(a) the main differences between the dB and dBA scales.
(b) what the reading would be for a sound of frequency 1 kHz if the meter was changed to the dBA scale.
(c) what would happen to the reading on each scale if the frequency of the sound was changed to 1.5 kHz.

Answer:

(a)

- The dB scale is not frequency dependent, so the output is the same at all frequencies
- The dBA scale is frequency dependent, so threshold intensities are different for different frequencies
- Frequencies on the dBA scale are adjusted to match the response of the human ear

(b)

- The reading on the dBA scale would be 80 dBA as 1 kHz is the reference frequency (at the threshold of hearing)

(c)

- The dB reading would be 80 dB as the power is constant (and dB scale is not frequency dependent)
- The dBA reading would be more than 80 dB as the ear is more sensitive at 1.5 kHz than at 1 kHz (or 1.5 kHz has a lower threshold intensity)

Exam Tip

Make sure you can draw the graph of intensity level in dBA against frequency - the key points to remember are

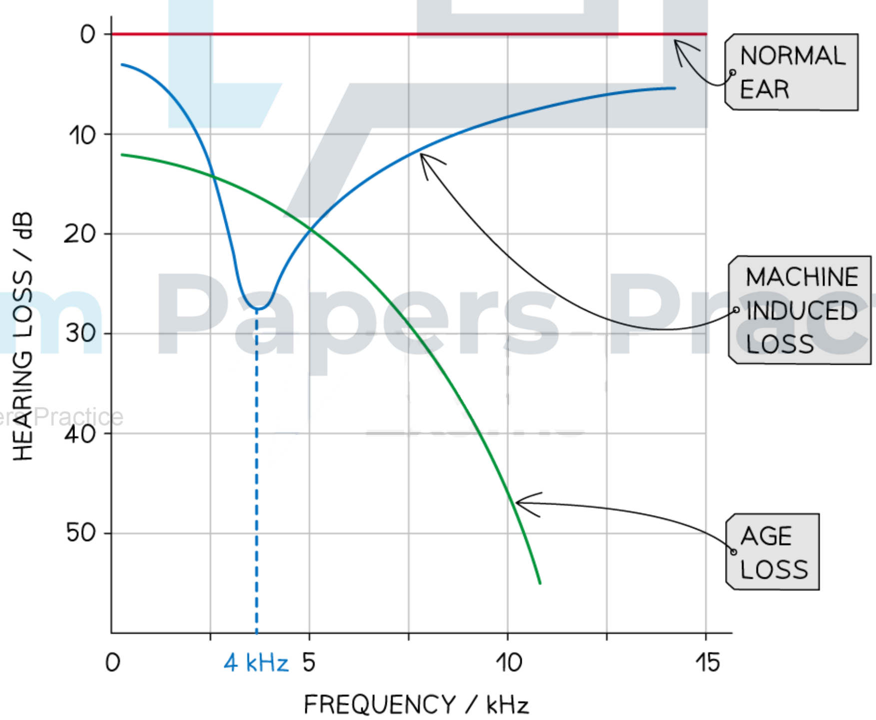
- The dB line is flat
- The dBA curve has the inverse shape to the equal loudness curve
- The dBA curve peaks at 3 kHz (frequency of maximum sensitivity)
- Both scales should have the same reading at 1 kHz (the reference frequency)

10.2.4 Defects of Hearing

Defects of Hearing

- Deterioration of hearing can occur due to
  - Age
  - Exposure to excessive and prolonged noise
  - Genetic factors and disease
- Depending on the type of hearing loss, the response is different for different frequencies of sound
- Hearing loss due to **ageing**:
  - Occurs at all frequencies
  - With the greatest losses at higher frequencies
- Hearing loss due to **excessive noise**:
  - Occurs in the frequency range the person was exposed to
  - With the greatest loss at 4 kHz

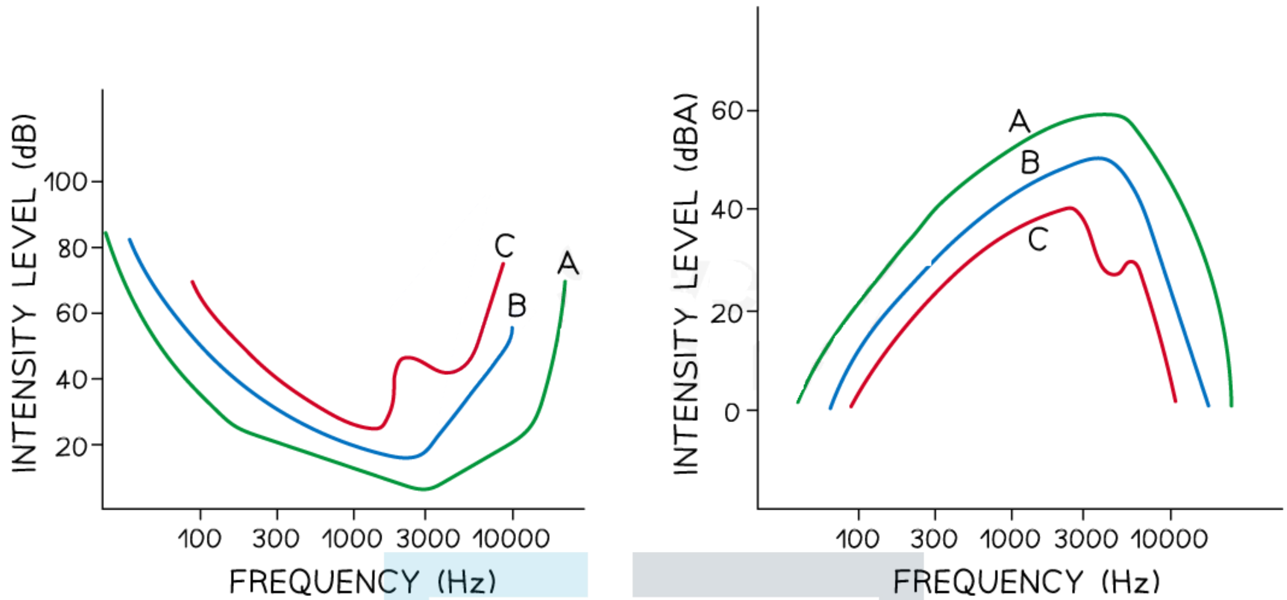
Hearing Loss & Frequency Variation



Depending on the type of hearing loss, different responses to frequencies of sound are found to deteriorate

- The degree of hearing loss can be tested by obtaining **equal loudness curves** and comparing the results with the curves for normal hearing
- The same, but inverted, curve can be obtained using **the dBA scale**

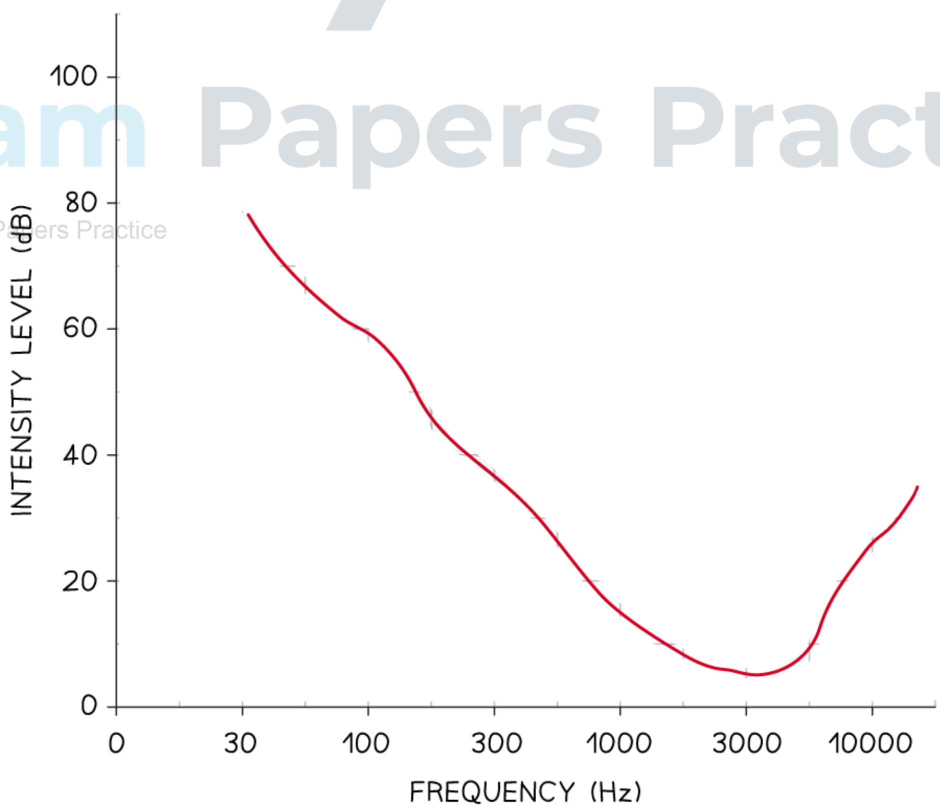
Comparing Hearing Defects



Curve A shows the response for a young person with no hearing loss. Curve B shows the response for an older person with hearing loss due to ageing. Curve C shows the response for a young person with hearing damage due to excessive noise

Worked example

A hearing test was used to obtain threshold hearing audiograms for a group of people. The diagram below shows the audiogram obtained for a person with normal hearing.



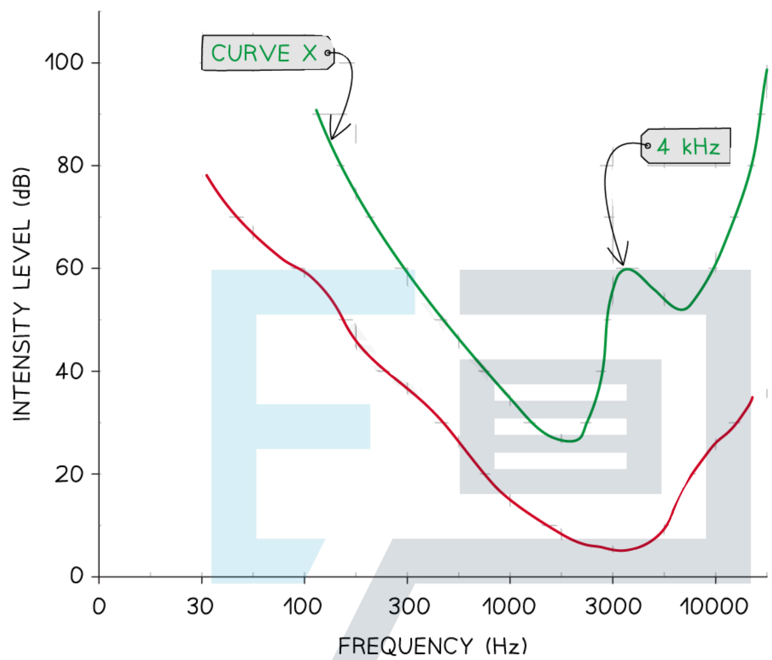
On the graph, sketch curves to show:

(a) a curve labelled X to show a person suffering from hearing loss due to excessive noise

(b) a curve labelled Y to show a person suffering from hearing loss due to old age.

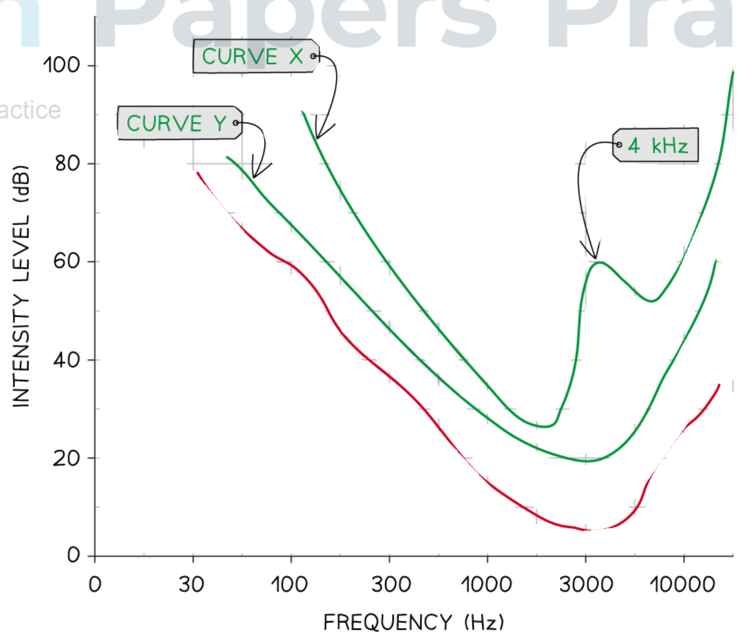
Answer:

(a) Hearing loss due to excessive noise



- Curve X: hearing loss increases up to 4 kHz then decreases after this frequency

(b) Hearing loss due to ageing



- Curve Y: loss increases as frequency increases