Engineering Psychology

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Week-03

Lecture-07

Auditory display - 1

Namaskar friends. Welcome to this seventh lecture in the series on engineering psychology. In the first six lectures, we explored the history of engineering psychology and the research methodologies used to solve problems in this field. We also examined visual displays, focusing on understanding the capabilities and limitations of the human visual system. We delved into the structure and functioning of the human visual system and discussed some of its inherent limitations.

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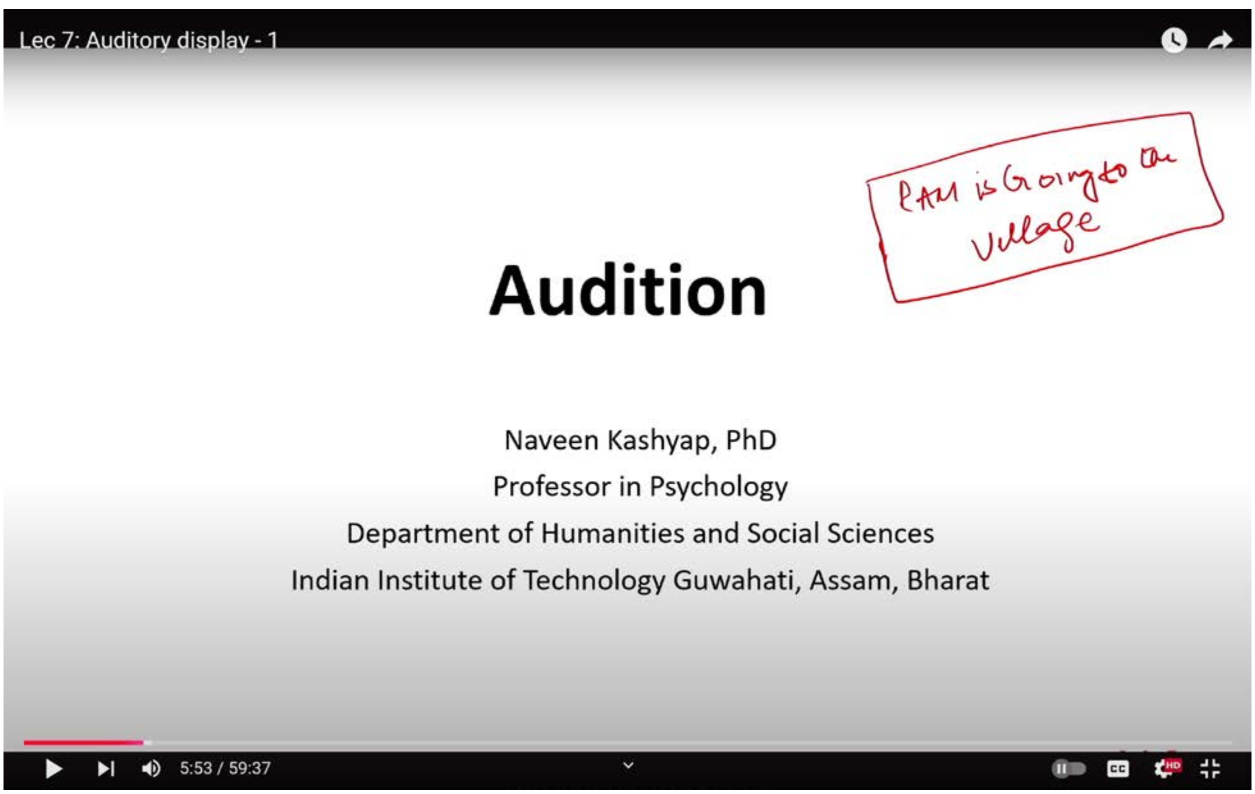

Furthermore, we discussed the design of visual displays, outlining best practices for creating displays that are efficient, legible, and visible, thereby providing enhanced support to operators. Towards the end of the last lecture, we briefly touched upon two other sensory display systems: the tactile system, related to the sense of touch, and the olfactory system, associated with the sense of smell. Building on that, today's lecture will focus in detail on the auditory sense. This lecture will be divided into two parts. In the first part, I will explain the human auditory system, covering its structure, functioning, and some fundamental principles related to hearing. In the second part, I will discuss how the principles, limitations, and capabilities of the human auditory system can be applied to the design of auditory displays and warning systems.

So, let us begin. Hearing, or audition, plays an essential role in human life. While the visual system is crucial for providing a large amount of information from the environment, aiding in daily activities, the auditory system complements it. In some aspects, the visual system is superior to the auditory system, but in other respects, the auditory system outperforms the visual one. One significant difference between the two systems is that vision allows for the presentation of a large amount of information in a very brief period. This enables quick encoding of information, but the processing of that information can take longer. If too much information is presented quickly, attention can shift, and some elements may be overlooked or filtered out.

On the other hand, the auditory system ensures that the listener pays full attention to the information being conveyed. Therefore, when a task requires focused attention, the auditory channels are more effective. While visual channels are fast, auditory channels are slower. Let me illustrate this difference with an example. Suppose I write the sentence, "Ram is going to the village." If I display this sentence to you visually, it is easy to read and understand, provided you are literate. You will quickly grasp that the sentence refers to a person named Ram who is performing the action of going to a place called the village. This entire sentence can be presented in a fraction of a second, and you can extract its meaning almost instantly.

Now, consider the same sentence spoken aloud. In this case, I would need to say it serially: first "Ram," then "is," then "going," and finally "to the village." Until the entire sentence is spoken, it has no complete meaning. For instance, if I stop after saying "Ram," the word has no actionable meaning, it is merely a noun. If I say, "Ram is going," it provides more information but is still incomplete. Only when the entire sentence is spoken do you understand the full meaning. Thus, while visual information can be delivered quickly, auditory information requires more time to unfold. However, this difference is not always a disadvantage.

A key limitation of the visual system is that it requires you to look directly at the stimulus. For instance, if visual information is presented behind you, you cannot perceive it. This limitation does not apply to auditory information. Sounds can be perceived from all directions, providing 360-degree awareness. Visual channels require direct line of sight, but auditory channels do not, they capture sounds from the environment regardless of direction. This example highlights how the visual and auditory systems differ and how each contributes to processing information in the world around us.

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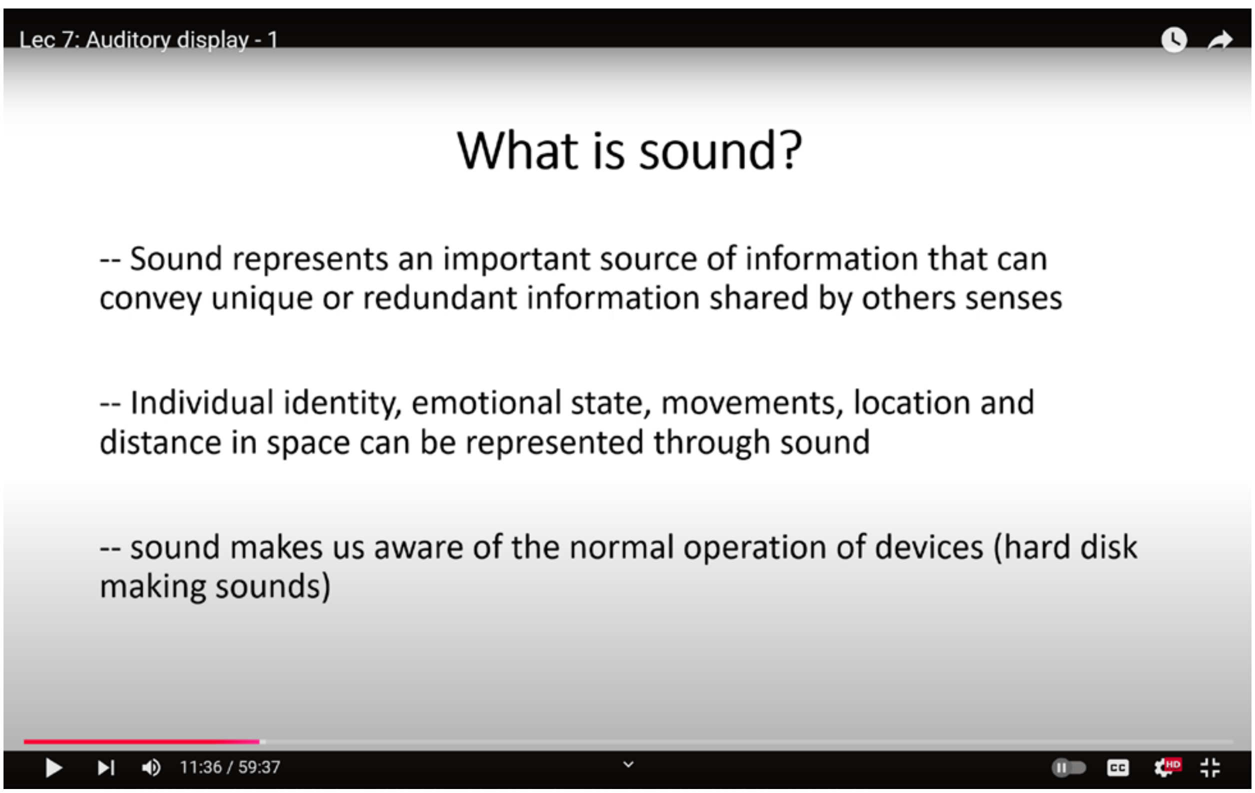

With this distinction in mind, let us start by understanding the auditory system in more depth. Why are visual systems important? Consider the example of crossing a road. You rely on your visual system to look for traffic signals, observe the road for a zebra crossing, and watch other pedestrians. You might press the button at a traffic light to signal that you want to cross, which prompts a traffic controller to enable the pedestrian light. In this scenario, you are primarily using your visual system to navigate. However, it is not the only sensory system in use.

You are also listening for sounds, such as the honk of a vehicle approaching too close, which may startle you into stopping your movement. Despite your reliance on visual signals, the auditory system provides an additional layer of awareness. It alerts you to things you might miss visually, reinforcing the information from your visual system. Therefore, the auditory channels are not just complementary to the visual channels; in some cases, they are crucial for avoiding danger.

Now, let us turn our focus to sound itself. Just as visual channels encode stimuli in the form of light, auditory channels encode stimuli as sound. So, what exactly is sound? Sound is a critical source of information, capable of conveying unique or redundant details that may not be available through other senses. For example, the warning signals in a car that remind you to fasten your seatbelt, the beeping sound when you reverse your vehicle, or the ding of a microwave oven when your food is ready are all auditory cues that provide important information, even if you are not looking directly at the source of the sound.

Sound conveys both unique and redundant information. Often, it supplements the information already provided by the visual system. For example, the ding of an elevator when it reaches your floor complements the visual display indicating the elevator's arrival. In fact, even after seeing the elevator has arrived, many of us wait for the sound as confirmation.

Thus, sound can deliver both unique and redundant information. It’s important to note that sounds are not limited to warning signals. If you close your eyes and listen to the sounds around you, you’ll notice a variety of auditory information. For example, by merely hearing people speak nearby, you can often discern who is talking, whether the speaker is male or female, whether they are a child or an adult, and even what emotional state they are in. Certain emotional characteristics are conveyed through sound, if someone is speaking quickly, they may be stressed, whereas a balanced tone with laughter between sentences likely indicates happiness. Sounds, therefore, convey not only identity but also emotions. A hearty laugh, a cry, or even a whizzing sound can all indicate emotional states. Additionally, sound can communicate movement and location.

For instance, when you or another object moves, it produces sound. The sound of a moving car, or even the sound of your footsteps, informs you of motion. Different locations also have characteristic sounds. For example, the soundscape of a quiet room is distinct from the bustling noise of a railway station. Therefore, locations and spatial distances can also be represented through sound.

In summary, sound conveys a wealth of information. It alerts us to the normal operation of devices and can serve as a warning system. Take a nearby computer: when functioning properly, it emits a particular sound. However, if the hard drive begins to make a scratching noise, you immediately realize something is wrong. Similarly, if the bicycle you are riding makes an unusual noise, you know the chain might have come loose and needs repair. Thus, sound not only conveys individual identities and emotions but also communicates the state of a system.

How is sound produced? Sound is generated by the vibration of an object or its surface. A classic example is a speaker or microphone. Many of you may recall older, large speakers often used at weddings. These speakers consist of a central magnet surrounded by a mesh, typically made of carbon fiber. As children, some of us would place liquid on this mesh. When the speaker played loudly, the liquid would "dance" due to the vibrations.

This illustrates how sound is produced: the outer surfaces of the speaker vibrate up and down due to the action of the magnet, causing the adjacent air molecules to vibrate. These vibrations propagate through the air and reach your ears, where the process of hearing begins. Essentially, sound is produced by the vibration of objects or their surfaces.

But how exactly does this happen? When a surface vibrates back and forth, it disturbs the air molecules next to it, creating regions of high and low pressure. These pressure variations then propagate away from the vibrating surface. This movement forms a simple sinusoidal wave, and if the object is something like a tuning fork or a musical instrument, it can create complex sounds. For simplicity, let’s consider a tuning fork. When struck, the tuning fork vibrates and disturbs the surrounding air molecules, transferring the alternating regions of low and high pressure through the air as a sinusoidal wave. This wave eventually reaches your ear, allowing you to hear the sound.

How is sound expressed? Sound is typically described in terms of vibrations, how many times an object, such as a tuning fork, vibrates in a given time. The number of vibrations an object makes in one second is called the frequency of the sound. Frequency is expressed in terms of vibrations per second, or Hertz (Hz). A "cycle" refers to one complete vibration, meaning how many times the object producing sound moves back and forth from a central axis in a given period. So, "cycles per second" refers to the number of pressure variations (or sound waves) generated in one second.

In terms of human experience, frequency corresponds to the pitch of the sound. The higher the number of vibrations per second, the higher the pitch. The intensity or loudness of sound, on the other hand, is related to amplitude, which refers to the height of the sound wave.

Most sound waves have two fundamental characteristics: frequency and amplitude. Frequency measures the number of vibrations (or cycles), while amplitude measures the difference between the highest and lowest points of the wave. In practical terms, frequency is experienced as pitch, and amplitude is perceived as loudness.

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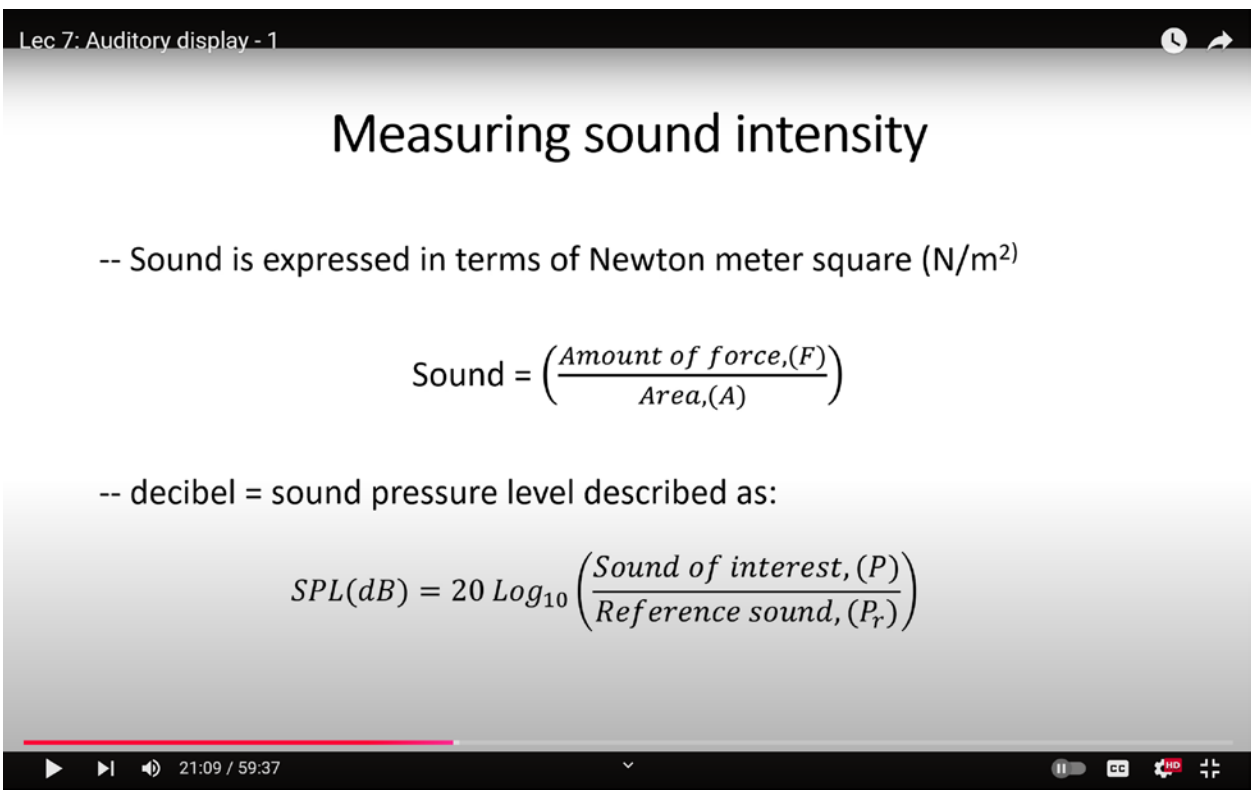

Now, how do we measure sound? The measurement of sound is based on the amount of force applied to create movement on a surface, expressed in Newtons per square meter. For example, if I tap lightly on this desk, you will hear a soft sound because the force my finger applies to the surface is small, and the desk area is large. However, if I hit the desk with more force, a louder sound is produced because the applied pressure increases while the area remains the same. So, sound is essentially the force applied over an area, expressed in Newtons per square meter.

However, this definition of sound can be difficult to apply to all sound measurements, which is why the decibel (dB) scale was devised. The decibel scale allows us to compare different sounds in terms of their relative loudness or pitch.

So, what exactly is a decibel? A decibel measures the sound pressure level, or the amount of pressure a sound exerts at any given time. The sound pressure level in decibels is calculated as the logarithm of the ratio between the sound of interest (P) and a reference sound (P_0), multiplied by 20. This equation provides the decibel value for any sound, enabling us to measure and compare different sounds accurately.

Now, we have simple sounds, such as those from a tuning fork, and complex sounds, like those produced by musical instruments. If you’ve ever listened to a tuning fork, you’ll notice that it produces subtle, simple sounds. However, the sounds around us are far from simple; they are a mixture of many different sounds. Thus, we can categorize sounds into two varieties.

The first variety includes simple sounds, like those produced by a tuning fork, which can be expressed as mathematically pure waves. The second variety includes complex sounds, such as those from musical instruments. These are classified as complex because they contain multiple sound frequencies. While the tuning fork vibrates at just one frequency, a musical instrument produces multiple frequencies in addition to the base frequency, making it a complex sound with varying amplitudes for each frequency.

So, how do we study a complex sound? Simple sounds are straightforward because they generate a single sinusoidal wave, which is easy to analyze. However, when multiple frequencies combine, they form a complex waveform, often resembling a square wave. To analyze such complex sounds, mathematician J.B. Fourier introduced the concept of breaking down any complex sound into its constituent simple frequencies. This process is known as the Fourier transform or Fourier transformation.

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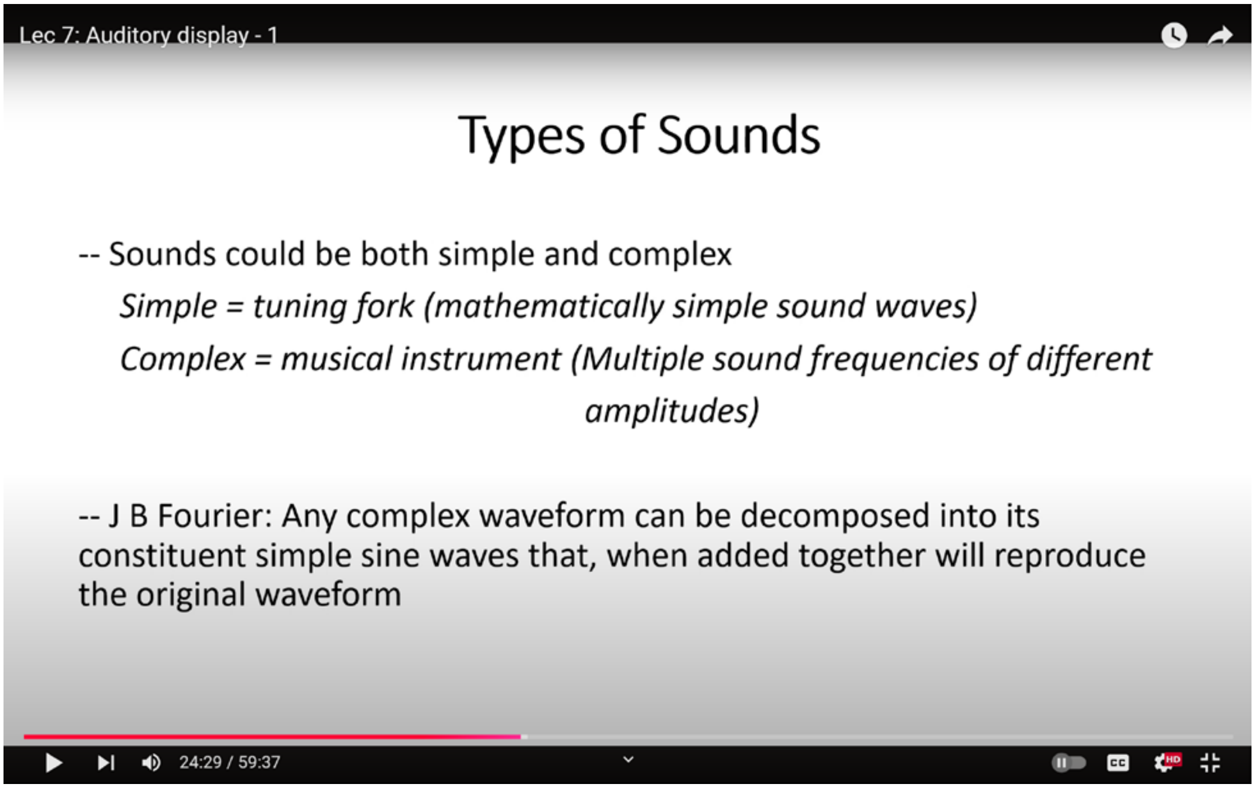

Fourier proposed that any complex waveform can be decomposed into its basic sine wave components, and when these simple waves are added together, they recreate the original complex waveform. This concept is elegantly explained in an MIT lecture that demonstrates how even the most complex sounds can be broken down into their constituent sine waves. If you get the chance, it's worth watching to better understand Fourier's theorem and how it applies to sound analysis.

Now that we've covered what sound is, let's turn to the human ear and its role in hearing.

The ear is composed of three main parts: the outer ear, the middle ear, and the inner ear. Sound first reaches the outer ear, specifically the pinna, which functions like a satellite dish, gathering sound waves and directing them into the auditory canal. The outer ear collects sounds from various directions and channels them into the auditory canal, which narrows as it approaches the inner structures. At the base of this canal are three small bones: the hammer (malleus), the anvil (incus), and the stirrup (stapes). These bones are connected to the tympanic membrane, commonly known as the eardrum. When sound waves strike the eardrum, it vibrates, and these vibrations are transmitted through these three bones to the inner ear.

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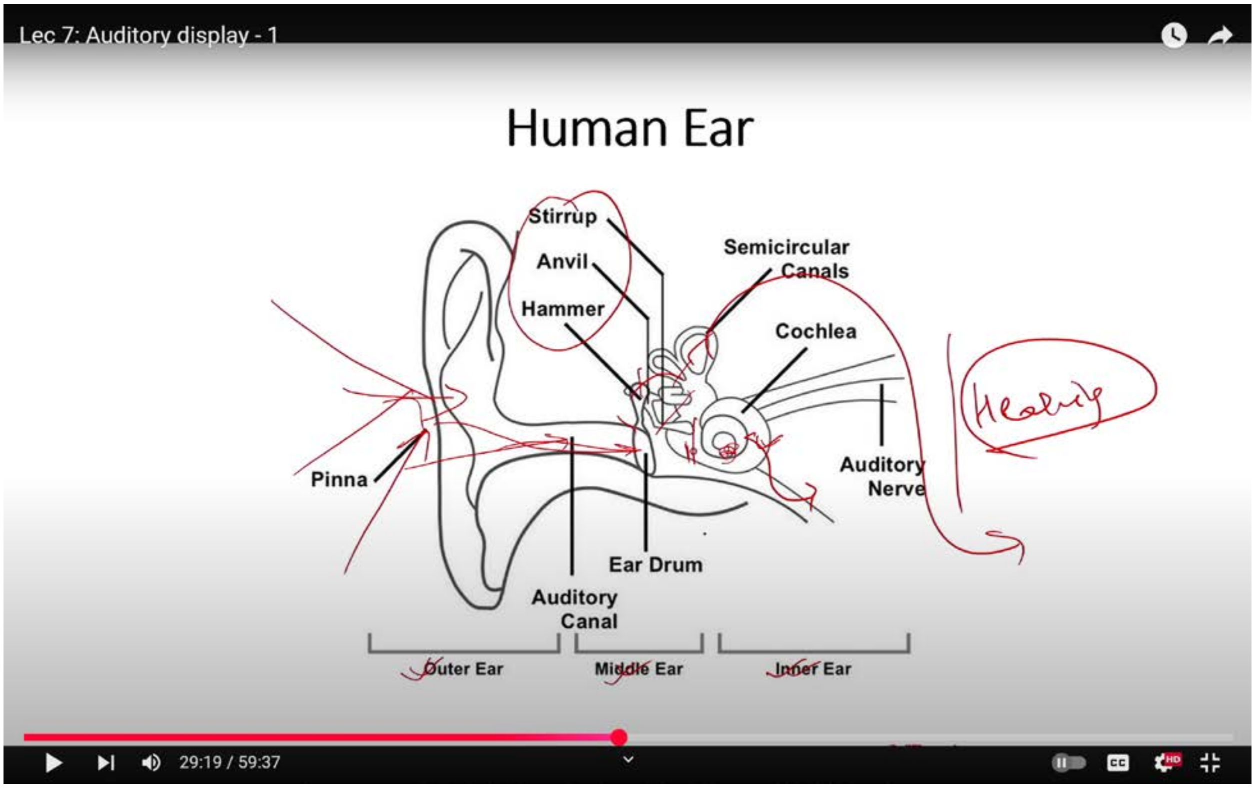

This entire process involves transforming air pressure variations into physical vibrations. The eardrum, like a taut membrane, vibrates in response to the incoming sound waves, and these vibrations are passed through the three tiny bones (ossicles) in the middle ear. These bones work as a lever system to amplify and transmit the vibrations to the inner ear, specifically to a fluid-filled structure called the cochlea, which is critical for hearing. The vibrations cause waves in the cochlear fluid, which stimulate hair cells along the basilar membrane, enabling the perception of sound.

In addition to hearing, the ear is responsible for balance through the vestibular system, which is closely related to the hearing apparatus. The vestibular sensory organ, located in the semicircular canals of the inner ear, contains fluid that helps maintain balance and spatial orientation. This system allows you to retain your position and adjust your movement according to changes in your environment.

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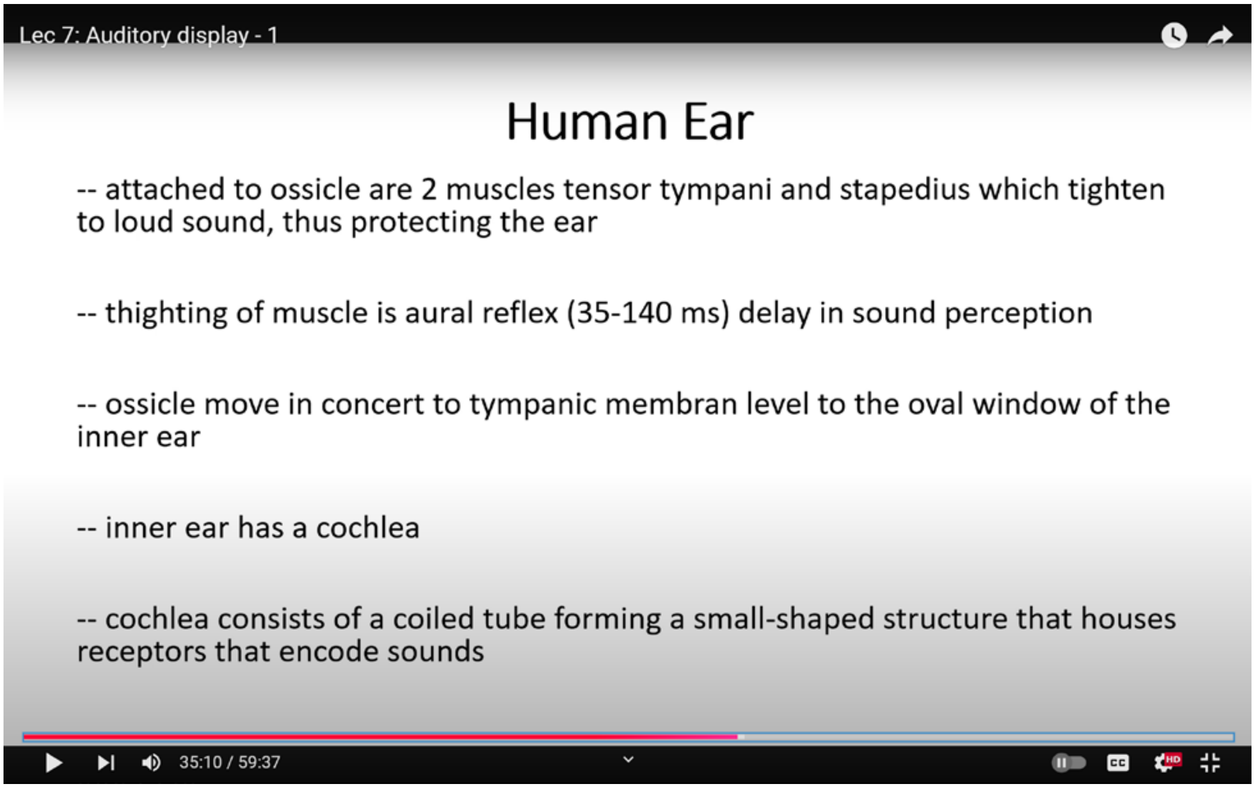

Let’s break down the ear’s structure and functions:

1. Outer Ear: This includes the pinna and the auditory canal. The pinna captures sound waves and directs them through the auditory canal towards the eardrum. As air pressure changes, they impact the eardrum, which vibrates in response.

2. Middle Ear: The middle ear houses the ossicles, the malleus, incus, and stapes. These tiny bones form a lever system that transmits the eardrum's vibrations to the oval window of the inner ear. The ossicles are crucial in amplifying sound and converting air pressure changes into mechanical movements.

3. Inner Ear: The inner ear contains the cochlea and the vestibular system. The cochlea converts the mechanical movements of the ossicles into fluid waves, which stimulate the hair cells on the basilar membrane, allowing us to perceive sound. The vestibular system helps with balance and

spatial orientation by sensing changes in head movement through the fluid in the semicircular canals.

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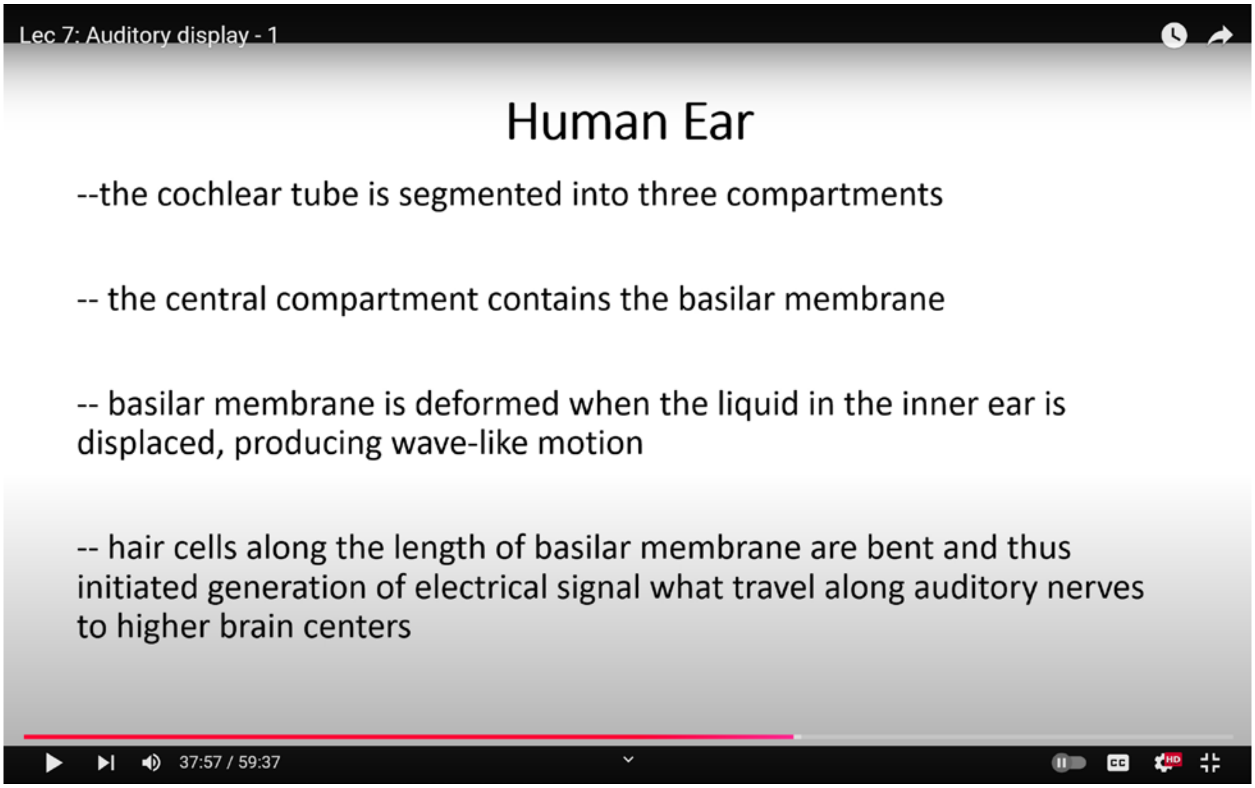

Connected to the ossicles are two muscles, the tensor tympani and the stapedius, which contract in response to loud sounds to protect the inner ear from damage. These muscles tighten when exposed to prolonged loud noises, a process known as the aural reflex. However, this response is slow, taking between 35 to 140 milliseconds, so it cannot protect the ear from sudden loud noises like a gunshot. The aural reflex is often tested by audiologists to diagnose hearing problems and determine the need for hearing aids.

Thus, sound enters through the outer ear, travels through the middle ear where vibrations are amplified, and is finally transmitted into the inner ear, where it is transformed into signals that the brain interprets as sound.

The ossicles function as a lever system, moving in concert with the tympanic membrane to transmit vibrations to the oval window of the inner ear. The inner ear contains the cochlea, which is a coiled structure. If uncoiled, the cochlea would be approximately 13 inches long and consists of three layers. Within the cochlea, a fluid flows, and it is in this region where sound perception begins.

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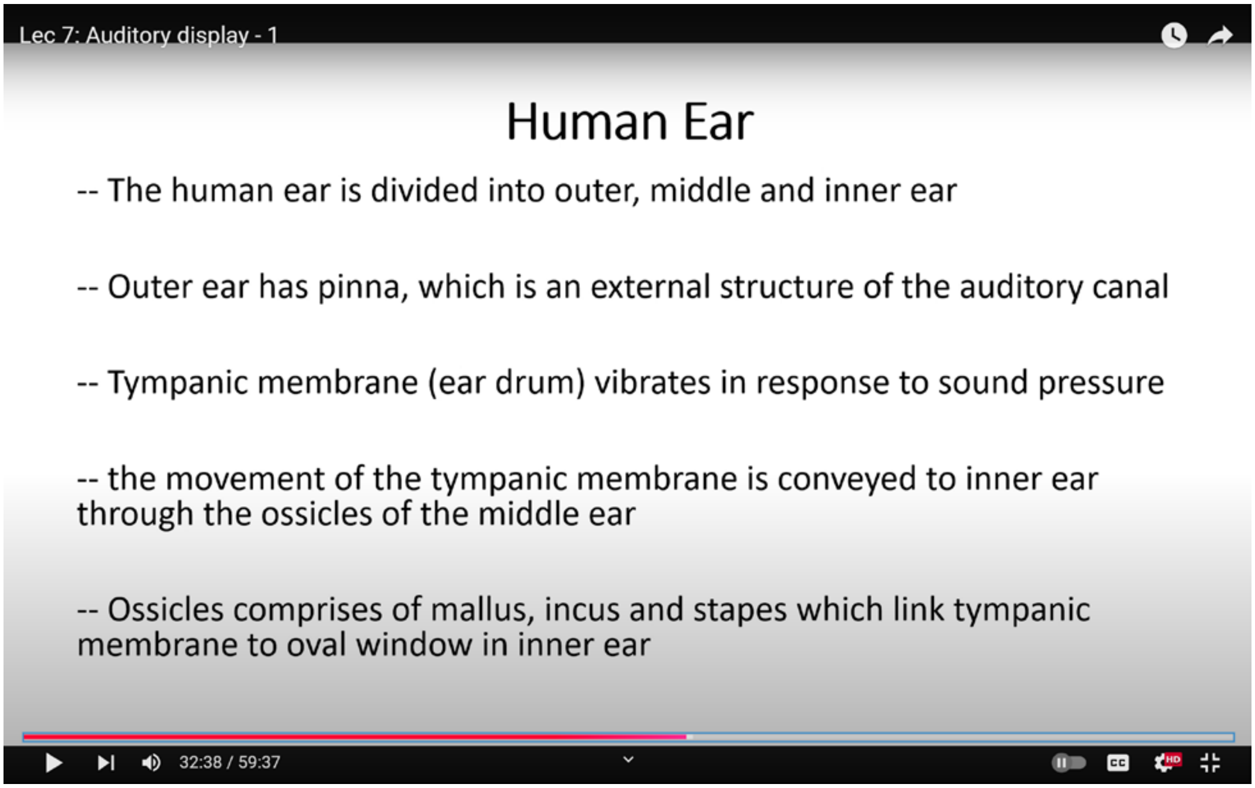

The cochlea is a coiled tube housing receptors that encode sound. Sound waves, initially transformed from air pressure into vibrations by the eardrum and ossicles, reach the cochlea, where these vibrations are processed. The cochlea is divided into three components, with the central part containing the basilar membrane. This membrane is crucial for hearing because it houses hair cells that detect the movement of the fluid. As sound waves travel through the cochlear fluid, they deform the basilar membrane, creating a wave-like motion. This motion bends the hair cells, initiating the generation of electrical signals.

These electrical signals are transmitted via the auditory nerve to higher brain centers, specifically the primary and secondary auditory cortices. The hair cells, along the length of the basilar membrane, convert the fluid's motion into electrical signals, which are then relayed through neurons called auditory nerves. These neurons transmit the information to the brain, where it is interpreted as sound.

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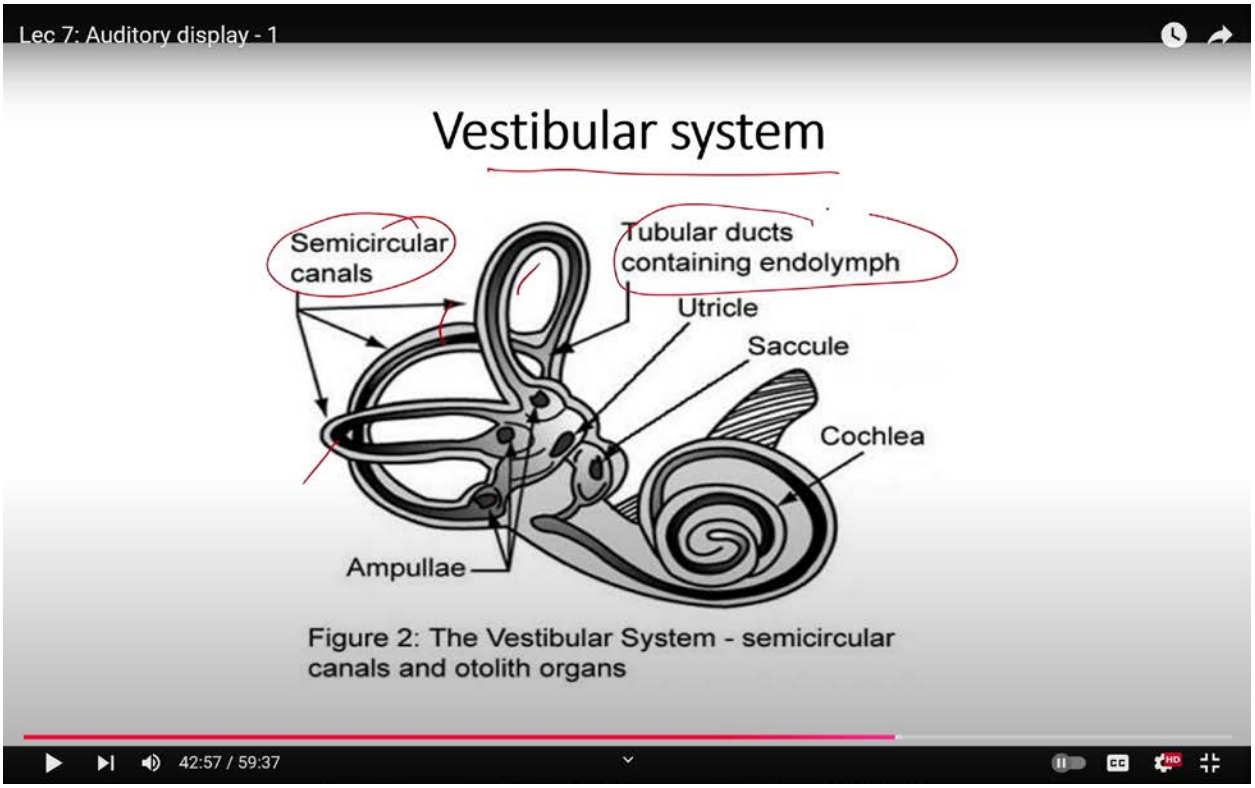

However, hearing is only one part of the auditory system. Another critical component is the vestibular system, which is responsible for maintaining balance and body position. Issues such as car sickness, motion sickness, or difficulty in maintaining balance arise when the vestibular system does not function properly. Along with hearing, the auditory system helps maintain equilibrium, particularly through the vestibular apparatus, which includes the three semicircular canals.

These canals, anterior, posterior, and horizontal, are part of the inner ear and are filled with fluid that aids in tracking head and limb movement, as well as maintaining body position relative to the ground and environment. These canals are arranged at right angles to each other, corresponding to the x, y, and z axes, and help monitor the body's orientation in three-dimensional space.

The vestibular system consists of several structures, including the three semicircular canals and the otolithic organs. These canals are hollow tubes filled with fluid, and they work in conjunction with the otolithic organs to provide information about the body's spatial orientation and motion.

This system ensures that you can navigate, walk, drive, or reach for objects with a proper sense of your position relative to external objects.

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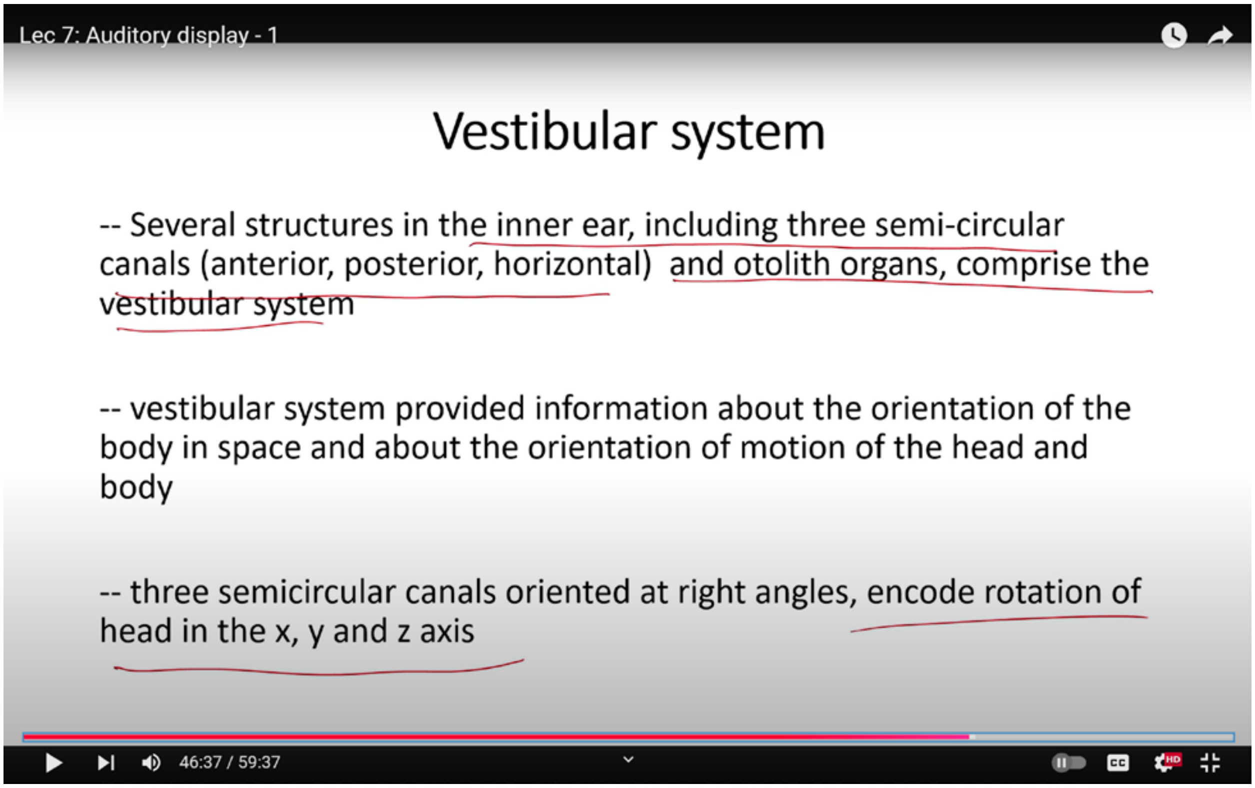

The vestibular system plays a crucial role in determining the body's orientation, whether upright or at an angle, and tracks the motion of the head. Head movement is particularly important in generating certain types of motion, as seen in movies where the movement of the eyeballs, along with head motion, produces the perception of motion. The vestibular system also assists in posture control, helping the body react to falls by preparing and minimizing the impact.

The three semicircular canals are oriented at right angles to encode the rotation of the head along the x, y, and z axes. Whether the head rotates side to side, up and down, or in and out, these canals detect and monitor the movement. Hair cells, known as stereocilia, within the semicircular canals detect acceleration and movement relative to external objects. These stereocilia are responsible for encoding the acceleration and motion detected by the vestibular system, ensuring accurate balance and orientation within space.

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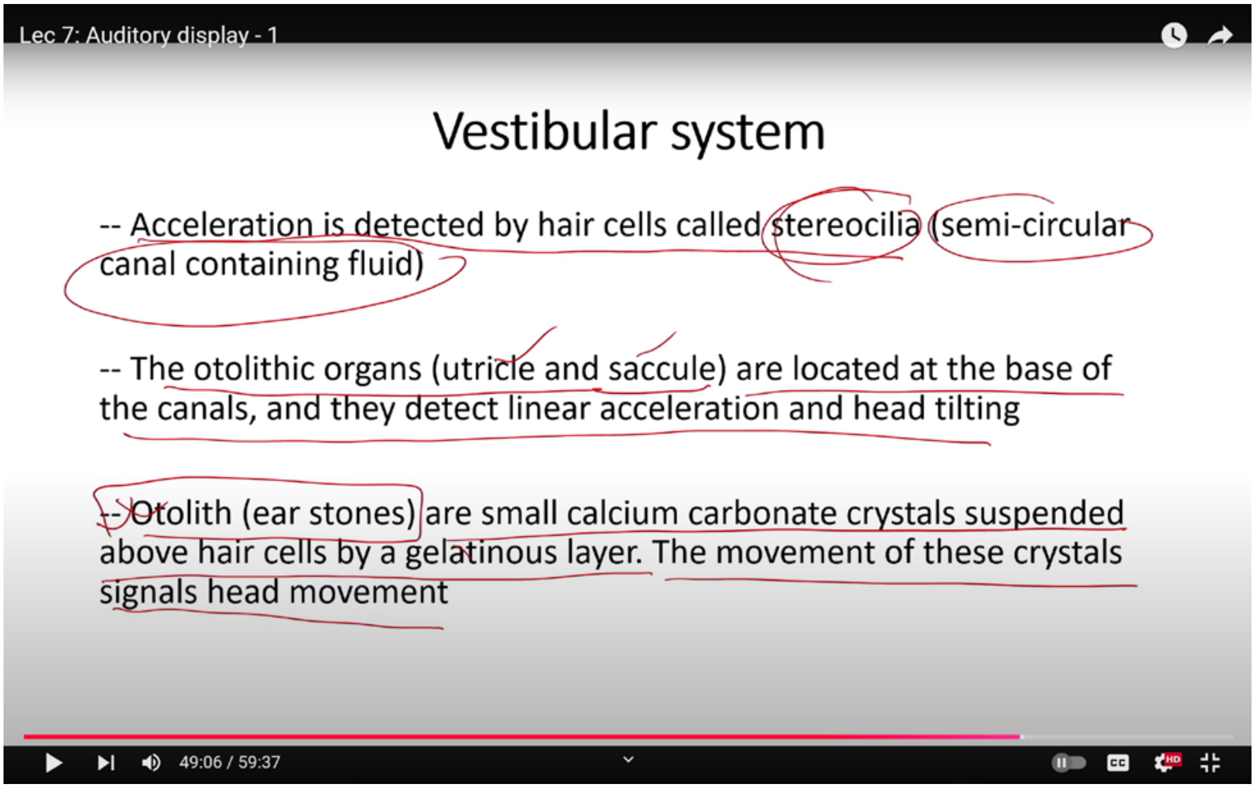

If these structures were absent, motion would not be encoded or understood. The otolithic organs, known as the utricle and saccule, as previously mentioned, are located at the base of the semicircular canals and detect both linear acceleration and head tilt. These organs are responsible for sensing head tilts in any direction as well as linear movements. The utricle and saccule, situated within the base of the otolithic organs, are specialized to perform this function. "Otolithic" refers to "ear stones." How do these organs code motion, similar to how the basilar membrane's hair cells encode sound patterns?

This occurs through the displacement of small calcium carbonate crystals. Let's delve into it. Otoliths, or ear stones, are calcium carbonate crystals suspended above hair cells in a gelatinous layer. When motion occurs, these crystals move, and since they lie atop the hair cells within the stereocilia, they move in response to the movement of the fluid inside the ear. As the head moves, the liquid moves, causing the crystals and hair cells to shift, signaling motion. This is how motion is detected by the system.

The vestibular system plays a vital role in maintaining balance, spatial orientation, and motion detection. People who frequently lose balance or fall often have issues with this system, while others with a properly functioning vestibular system can break their falls by using countermeasures or reflexive body movements. These counter-body movements are initiated through the vestibular system.

In terms of spatial awareness, the vestibular system helps orient oneself. For example, when looking at a map, it helps individuals identify directions such as north or south. Some people find it easier because their vestibular system provides reliable information, while others may struggle. Motion is also encoded by the vestibular system, particularly by the hair cells within it.

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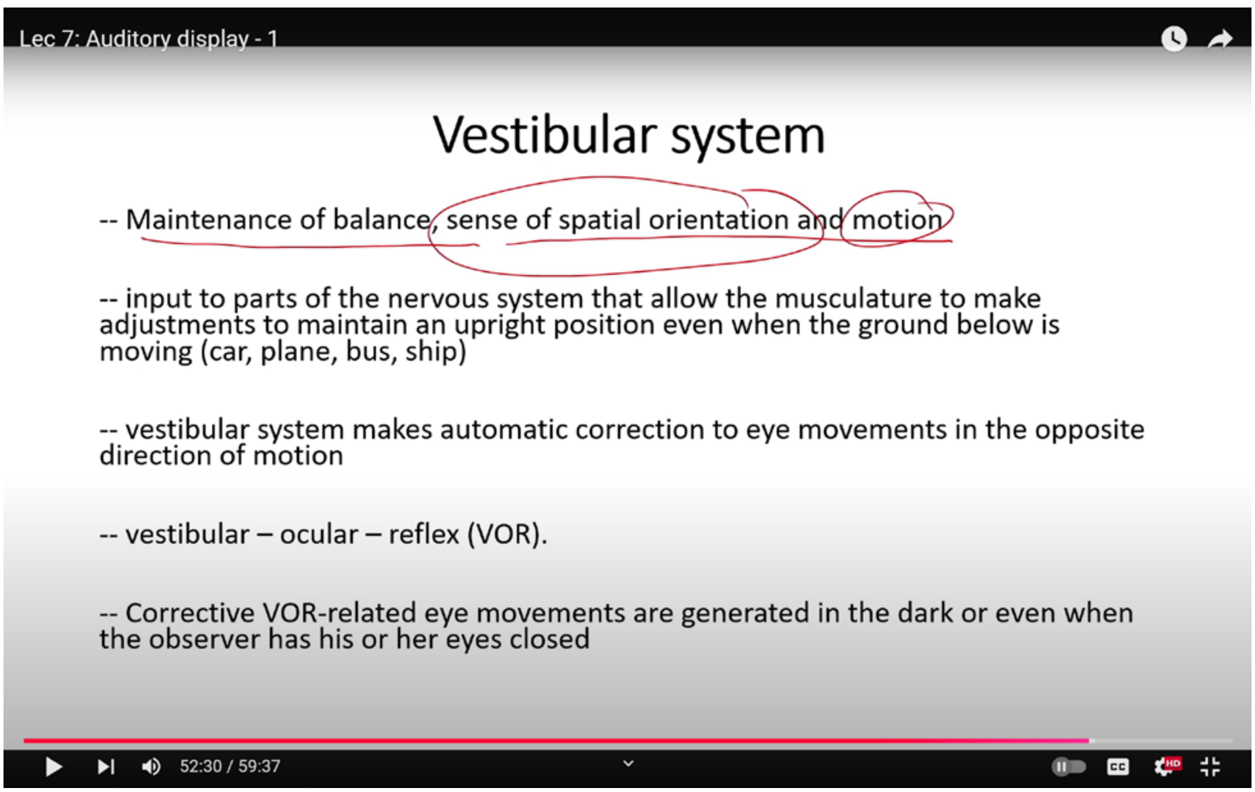

The vestibular system sends input to parts of the nervous system, enabling the body's musculature to make adjustments to maintain an upright position, even when the ground beneath is moving. For instance, when sitting in a moving vehicle like a car or airplane, the vestibular system adjusts the body's position to maintain balance, preventing you from falling despite the motion of the vehicle. The system provides feedback to the nervous system, facilitating these muscle adjustments to keep the body stable even in motion.

Additionally, the vestibular system automatically adjusts eye movements in the opposite direction of motion, a phenomenon known as the vestibulo-ocular reflex (VOR). For instance, while traveling in a moving car, when you focus on a billboard, your eyes compensate for the car's motion to maintain focus. The vestibular system helps synchronize the motion of your eyes with the speed of the moving vehicle, ensuring stable vision. This reflex is called the vestibulo-ocular reflex, which makes corrective eye movements to maintain focus on an object while the body is in motion. Interestingly, this reflex occurs even in complete darkness or when your eyes are closed, showing that visual perception is not necessary for VOR to function.

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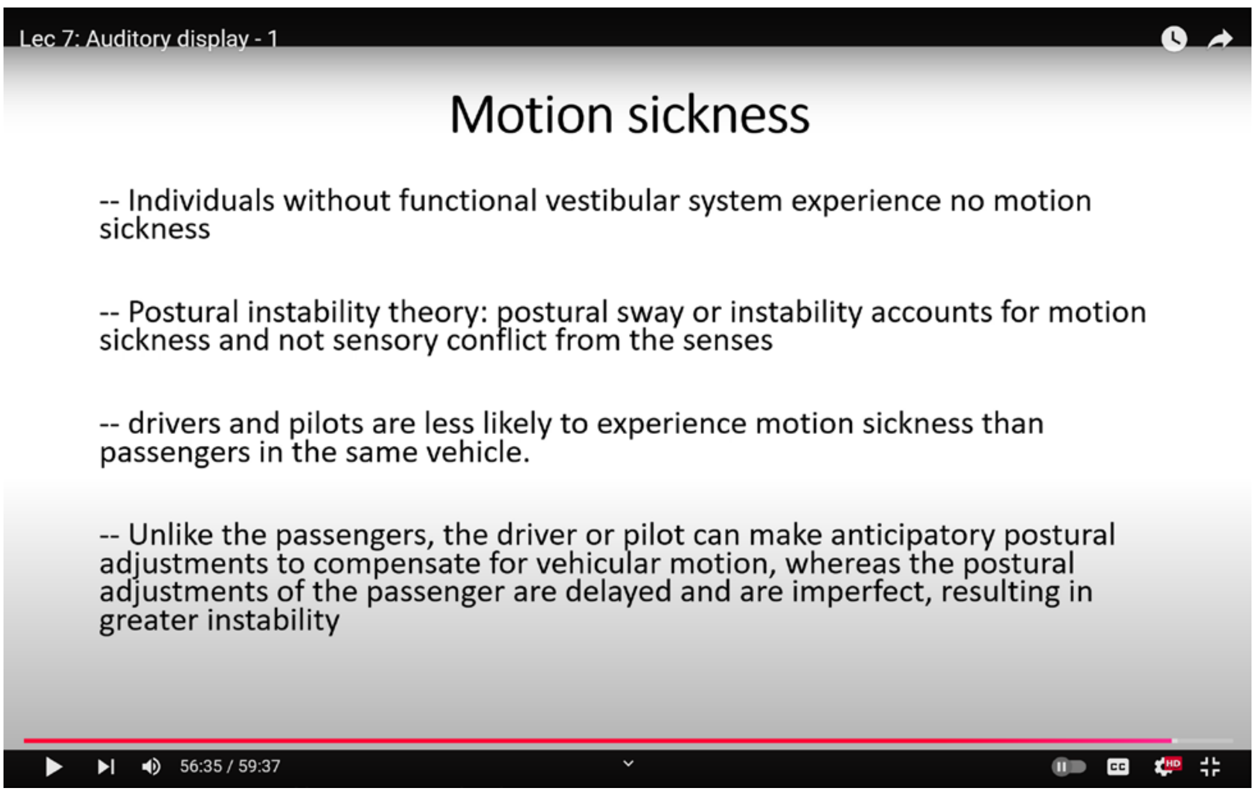

Motion sickness is another issue directly related to the vestibular system. Many people experience discomfort in moving vehicles such as cars, buses, or airplanes. Symptoms can include nausea or even a ringing sensation in the ear. This is known as motion sickness. By now, you may have guessed the reason behind this phenomenon.

One explanation for motion sickness is the conflict between two different sensory cues. For example, while sitting in an airplane, the vestibular system may signal that the body’s position is changing, but when you look at your feet, you may not perceive that change. This conflict between the vestibular and visual cues can cause discomfort, leading to motion sickness. Sensory conflict theory suggests that motion sickness arises when vestibular motion cues, like the airplane turning, conflict with the visual cues from the eyes, which may signal no apparent movement. Notably, individuals who lack a functional vestibular system do not experience motion sickness.

Another theory explaining motion sickness is the postural instability theory. This theory posits that body sway and instability are the main causes of motion sickness, rather than conflicting sensory information. According to this theory, it is the instability of the body’s posture and movement that accounts for motion sickness. A common example is that drivers or pilots are less likely to experience motion sickness compared to passengers. The reason is that drivers or pilots can anticipate changes in the vehicle’s motion, allowing them to make adjustments in posture before the movement occurs. Passengers, on the other hand, cannot anticipate these changes, leading to delayed postural adjustments and an increased likelihood of motion sickness.

In conclusion, today's class covered the auditory and vestibular systems and their roles in balance, motion detection, and spatial orientation. In the next session, we will explore the limitations and capabilities of the human auditory system, focusing on how sounds are perceived and processed. We will examine how the cochlea codes pitches and frequencies and how different sounds are compared in the brain. Additionally, we will look at how auditory displays are designed and discuss principles for creating efficient auditory warning signals that enhance performance without causing confusion. That wraps up today's lesson. Thank you and Namaste!