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Improving Demonstration Models for Otology Education

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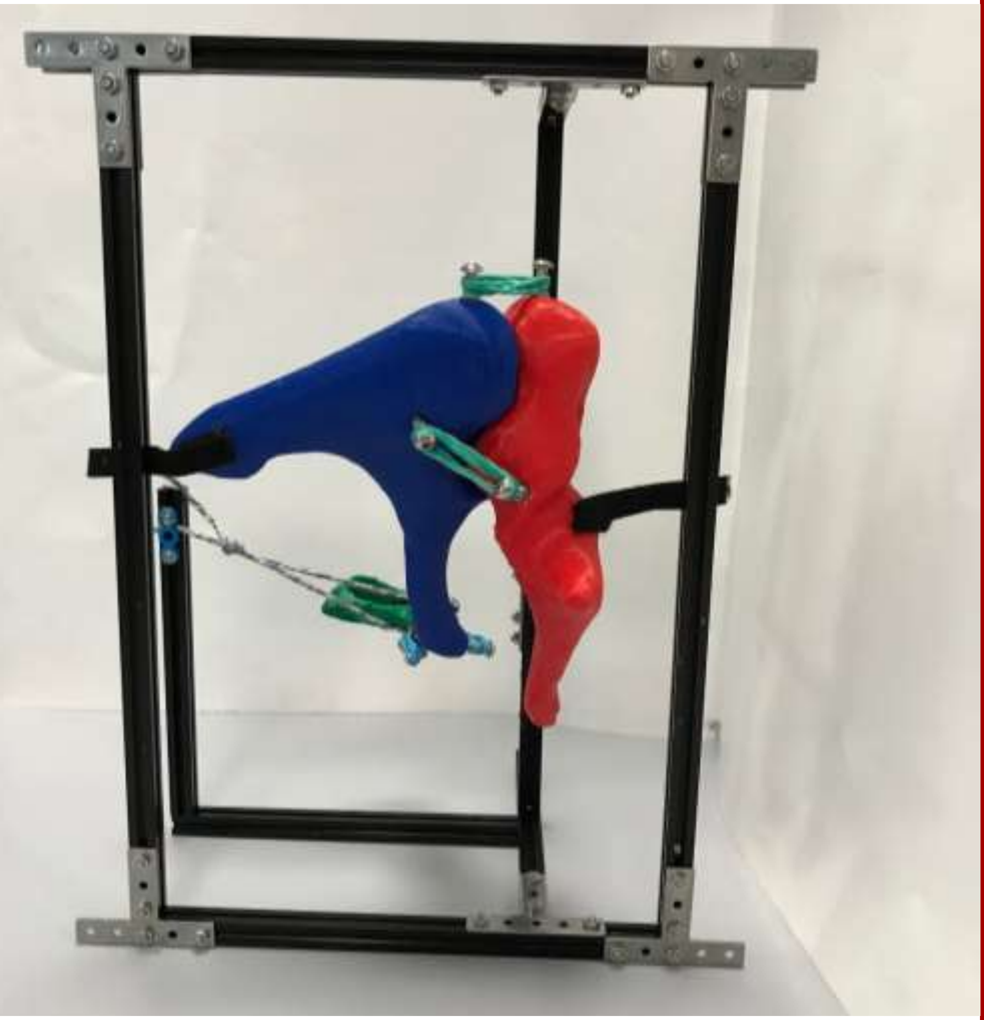

Interactive Qualifying Project

Sponsor:	UniversitätsSpital Zürich
Liaisons:	Ivo Dobrev, Postdoctoral Researcher, USZ
Advisor:	Blake Currier, Ph.D., Department of Physics
Co-Advisor:	Creighton Peet, Ph.D., Interdisciplinary and Global Studies Division
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Improving Demonstration Models for Otology Education

An Interactive Qualifying Project Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE in partial fulfilment

of the requirements for the Degree of Bachelor of Science

Submitted to:

Sponsor: Ivo Dobrev, Postdoctoral Researcher, USZ

Advisor: Blake Currier, Ph.D., Department of Physics

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Date: 11 Oct 2019

Abstract

Our project involved improving student understanding of hearing mechanics and providing UniversitätsSpital Zürich with recommendations on how to develop more effective teaching models. Through research, we found the importance of having an interactive model for teaching and a physics reference sheet to increase student understanding of hearing mechanics. We utilized the software Amira, Geomagic, and Solidworks to isolate the ossicles from Micro-CT scans of the ear to create a 3D model. Our model should benefit student understanding of the middle ear.

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Authorship

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Introduction	Sarah Vasquez	Dan Seeley
Background	Nazanin Beigi	Sarah Vasquez
Methodology	Sarah Vasquez	Colin Scholler
Results & Analysis	Sarah Vasquez	Dan Seeley
Conclusions & Recommendations	Sarah Vasquez	Colin Scholler
Appendices	Nazanin Beigi	Dan Seeley
Technical Leads for Model	Colin Scholler	Dan Seeley

Table of Contents

Table of Figures

Table of Tables

Executive Summary

Roughly 466,000,000 people suffer from debilitating hearing loss worldwide (WHO, 2019). Despite these statistics, hearing aids are still unaffordable for most developing countries, which contribute the most to debilitating hearing loss worldwide. To address hearing loss, physicians and researchers must understand the ear and how sound travels through it. In order to understand these complexities, they need to utilize interactive models to improve teaching methods.

Anatomical teaching models have largely gone unchanged from the first plastic models introduced in the early 1950's (Fredieu et al., 2015). When teaching about more specialized topics, such as otology, static anatomical models are insufficient and outdated and fail to depict the relationship between the ear and soundwaves. Additionally, current models show idealized anatomy without variation from disease or infection. Physicians often have difficulty understanding how ailments can affect the relationship between soundwaves and the middle ear.

Interactive teaching models result in higher retention and stronger in-depth student understanding of concepts (Yammine & Violato, 2016). Although static models are ideal for learning human anatomy, they lack anatomical variation, mobility, and functionality. Surgical models are the most realistic models because they try to imitate live tissue response, but lack mobility and variation in size, shape, and showing dysfunctions of the ear caused by infections.

The goal of this project was to provide UniversitätsSpital Zürich (USZ) with recommendations on how to make middle ear models more interactive to improve otology education.

To achieve this goal, we developed three objectives:

1. Determine the effectiveness of current teaching methods and models for the middle ear at UniversitätsSpital Zürich.
2. Identify the shortfalls of current middle ear models that are important to students and professors.
3. Create and identify how to make a more mechanically and physically accurate middle ear models for improving the understanding of ear functions.

In order to complete these objectives, we conducted nine semi-structured interviews with professors, graduate students, researchers, physicians, and a biomedical company. These interviews helped us determine that the ossicles would be the most beneficial area of the middle ear to model for physicians, researchers, and students. Our sponsor, Dr. Ivo Dobrev, is a postdoctoral researcher studying hearing mechanics. He helped recreate a lecture from the ear, nose, and throat (ENT) department so we could observe the UniversitätsSpital Zürich ENT department's teaching methods. For our model, we utilized Amira (version 6.1.1, 2016) to isolate the ossicles from Micro-CT scan data and Geomagic Design X (version 5.1.0.0, 2014) to remove soft tissue from the ossicles, filling in any gaps in the bone structure in the process. SolidWorks (version 26, 2017) allowed us to connect the ossicles together and scale our model 20 times larger than the average physical size before 3D printing.

We found from interviews with professors and students, that teaching methods within graduate courses rarely include interactive models. However, professors and students both expressed a desire for more interactive models to improve the understanding of hearing functionality and mechanics.

To understand the physics behind hearing, students first need to understand basic physics concepts such as sound waves and frequency. We recommend that otology courses at USZ implement physics reference sheets so students can reference the sheet during ENT department lectures. A reference sheet would be helpful since textbooks are not the basis of ENT department lectures. The reference sheet should focus on the types of sound waves such as longitudinal and standing waves. Further, the sheet would briefly reference the basics of frequency and amplitude. In addition to reference sheets, utilizing interactive websites to visually demonstrate travelling soundwaves can further student understanding of these concepts.

We found that professors, graduate students, and physicians think the ossicles are the most important structure of the ear to model. Widely used static models allow the anatomy of the ear to be seen very clearly, however, these models are unable to show any anatomical responses to stimuli such as sound waves. Further, static models on a large scale show the ossicles clearly but are not portable enough to be brought to the ENT departments lectures. The ossicles are important to model due to their movement regarding frequency. Accurate modeling of the ossicles would help student understanding of sound waves and frequency. Current models are not focused on mobility but rather the anatomy.

The movement of the ossicles changes with different wave frequencies. We developed a model to begin to show how frequency affects the ossicles and help students to understand this mechanical relationship. We also recommend that USZ make models that show variation in anatomy and diseases of the middle ear.

We found from interviews with researchers and physicians the importance of incorporating anatomical variation and mobility of the ossicles. Anatomical variability within a model would entail variation in size, shape, and ailments that negatively impact the ossicles. From these findings, we chose to utilize elastic bands to represent the joints between the ossicles since the tension could be manipulated to represent infection. Additionally, the model we created can depict the movement of the ossicles regarding various frequencies.

Our team created a physical model that can be used to demonstrate how vibrations travel through the ossicles and how the ossicles' range of movement changes with frequency. We used 3D modeling software to extract and design the model and 3D printing to make the hands-on model. We recommend that USZ add more components to the model that our team created such as a functional cochlea, tendons, and soft tissue to show how sound travels through the ear. We also recommend that USZ consult with biomedical companies to explore more materials and processes, other than 3D printing, for making ear models.

Our project is important because our interactive model will help improve educational methods to graduate students, researchers, and physicians about how humans hear different frequencies of sound waves. Graduate students going into research or surgery will be able to visualize the movement of the ossicles and physicians can be more aware of how hearing loss occurs. Through our interactive model, more awareness about the ossicles' movements can be better understood.

1 Introduction

Currently, in the United States about 37.5 million individuals over the age of 18 have reported hearing troubles (NIH, 2016). For every 1,000 children born in the United States, approximately 3 are born with some form of hearing loss. In Switzerland it is estimated that approximately 600,000 in the 6-million-person population are hard of hearing (Leybold-Johnson, 2018). Further, the World Health Organization (WHO) estimates that 466 million people world-wide suffer from hearing loss (WHO, 2019). Data from the WHO also suggests that by 2050 over 900 million individuals will suffer some degree of hearing loss. The number of people affected by hearing loss represents how important it is for medical students and physicians to understand how humans hear. Not only do physicians and medical students need to know the basic functions involved with hearing, but the abnormalities must also be understood in order to identify the reasons for dysfunction. This makes the study of otology and the physics behind how we hear critical for treating hearing loss for millions of individuals.

Although graduate level education within medicine and biology has been improved in recent decades through technology, teaching models in otology are still lacking critical details. Despite improvements to anatomical models, otological models are incapable of accurately demonstrating key concepts for students studying otolaryngology (Paolis, 2017). Models within otology are typically static, digital, or a simulation for medical students to practice on for surgery. Static models provide little to no movement and only feature the idealized anatomy of the ear. Digital models are advantageous in accessibility and manipulation which allows students to see different angles. Phacon, a biomedical modeling company, creates simulations of the temporal bone and inner ear so students can practice surgeries and see if they have severed a nerve. However, these types of models all lack one commonality: the physics behind how we hear is not depicted. Otolaryngological models need improvements to depict how sound waves and acoustics are received by the human ear and how it enables hearing. Such models have the potential to help students of otology understand hearing loss better than traditional educational methods.

Recently, the number of hours required to study gross anatomy has decreased largely due to the use of models (Leung et al., 2006). In 1955, the average number of hours for teaching gross anatomy in a 4-year medical school was 330 hours, while in 1997 that number decreased to just 165 hours. Anatomical models allow students to investigate parts of the body, such as the nervous and skeletal systems, without having to rely on the low supply of cadavers. The current otological models primarily focus on the easily labeled parts of the ear. These models do depict the middle ear; however, they do not provide great insight into the mechanical forces acting on these parts of the hearing system. Recently, a team of researchers in Japan has worked to develop an improved model of the inner ear, however this model is not available to the public (Nogueira & Cruz, 2010). Although other countries pursue research in otology, researchers are still addressing problems in the field. Currently, there are limited teaching models that specifically demonstrate how hearing is achieved through the physics principles that underpin the functioning of the middle ear.

In order to better understand how we hear, students must understand the basics of physics. This includes sound waves, interference between waves, nodes, frequency, overtone, and superposition (Somayaji, 2015). Current static models, despite their anatomical correctness, do not take into account any of the external stimuli acting on the ear. This is the area of improvement that researchers need to address (Keefe, 2015). Our sponsor, UniversitätsSpital Zürich (USZ), currently uses models for teaching otology that are not appropriate for demonstrating all aspects of our hearing system. This is due to a lack of research on interactive models of the middle ear that incorporate physics concepts such as waves and oscillations.

The goal of this project was to make recommendations and create a more effective middle ear model to improve the educational understanding hearing mechanics. To complete this goal our team achieved a set of objectives. These included determining the effectiveness of current teaching methods and models, identify the shortfalls of current middle ear models, and creating an interactive middle ear model for improving the understanding of ear functions. The project team interviewed various professors, physicians, and graduate students within the field of otolaryngology. Through these interviews, our team learned that reviewing physics concepts in lectures at USZ is time consuming and results in limited understanding by students. Students and physicians have made it clear that a model that demonstrates movement in the middle ear would benefit student learning. We created a physical model using Micro-CT data and 3D printing to better show the physics behind the middle ear. Our project has contributed to the field of otology education by creating an interactive model to be used during ENT lectures.

2 Background

Currently, the models used within the field of otology only depict the anatomy of the ear. Our sponsor, Dr. Ivo Dobrev of the Biomechanics of Hearing lab at USZ, is innovating new methods to teach graduate students about hearing through the principles of physics and mechanics. This chapter discusses the history of otology, current educational ear models, basic physics behind hearing, and an in-depth look at the middle ear, which our project focused on. Additionally, included is an overview of teaching styles and student learning preferences that highlighted what is needed in a model of the middle ear.2.1 The Field of Otology

2.1 The Field of Otology

Otology is the study of the anatomy and diseases of the ear, such as hearing loss (Mayo Clinic, 2019). The study of otology enables doctors to properly treat ailments of the ear and understand the mechanisms behind our sense of hearing. Otology is a subset of Otorhinolaryngology (ORL), or the study of the ears, nose, and throat (ENT). Often an otorhinolaryngologist is known as an ears, nose, and throat specialist.

2.2.1 History of Otology

The study of otology began around 2500 B.C., with Edwini Papyrus, a battlefield medic (Somayaji, 2015). Papyrus had started to keep documentation of battle injuries on the temporal region and the effects it had on soldiers hearing ability. By 1500 B.C., multiple specialists had collaborated on their findings and made significant progress in otology. In 460 B.C., Hippocrates, “The Father of Medicine”, advanced the study of otology through his discovery of the temporal membrane. From Hippocrates’ discoveries and influence, otology achieved greater respect and focus throughout the medical community.

2.2.2 Otology in Present Day

Within the past century, otolaryngology was not a focused specialty. In fact, a recent survey conducted by PubMed presenting data of over 1,000 primary care residents showed that many residents are not aware otolaryngology is a specialty (Hu & Meyer, 2012). In addition, only 43% of patients are aware of what otolaryngologists are. By analyzing the misperceptions of the role of an otolaryngologist, the current specialists hope to improve otology education.

There are currently about 120 otolaryngology residency programs in the U.S. (Doximity, 2019). In recent years, the number of residency candidates interested in otolaryngology has fallen (Hamaker, 2018). In 2018, only 303 out of the 315 available positions were filled. There are many possible factors that influence this decrease, such as the difficulty of otolaryngology programs and a “lessening of the specialty’s presence in current medical school curriculum” (p. 32). Therefore, the field of otolaryngology could benefit from stronger medical school and residency programs.

2.2 Biology of the Ear

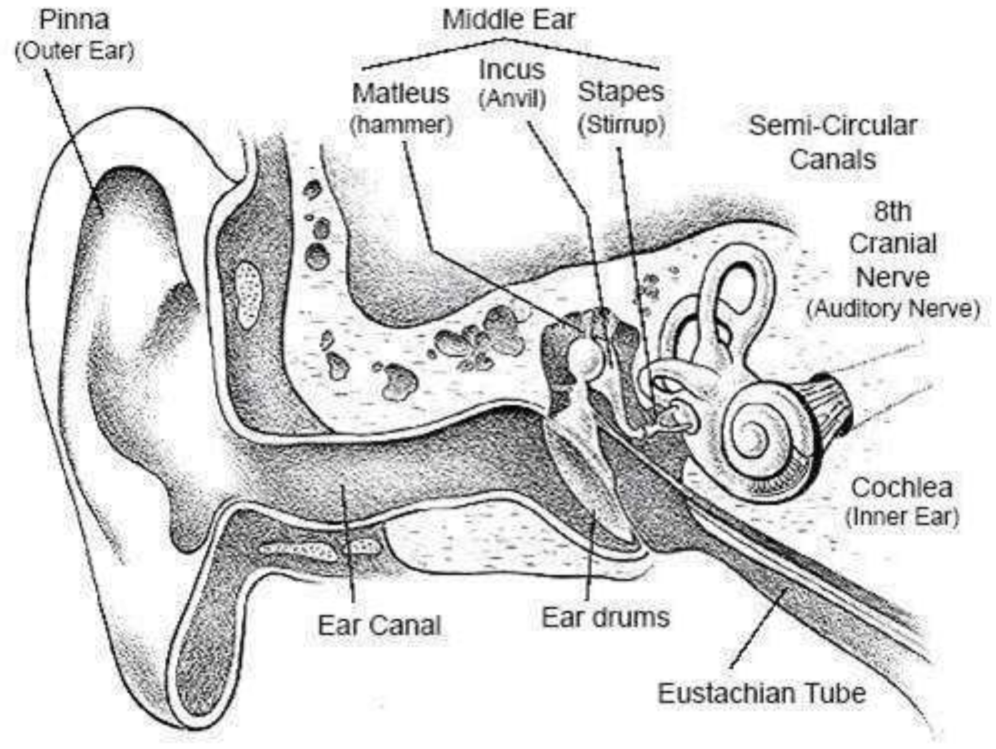


Figure 2.1: Anatomical visual representation of the ear. (Source: Alberti, 2004, p.54)

Human ears have many anatomical complexities that are sensitive to vibrations and sound waves (Alberti, 2004). The major function of the ear is to detect, transmit, and transduce sound as a sensory organ. The parts of the ear responsible for hearing and that are related to our project are:

- **Tympanic membrane (eardrum)** – The tympanic membrane divides the external ear from the middle ear (Alberti, 2004). This membrane vibrates in response to sound waves.
- **Ossicles** – These are the three small bones located within the middle ear (tympanic cavity). They transmit sound waves from the tympanic membrane to the inner ear

(Alberti, 2004). The bones are the malleus, incus, and stapes (also known as the hammer, anvil, and stirrup, respectively).

- **Eustachian tube** – This is the canal that links the middle ear with the back of the nose. It allows the pressure in the middle ear to equalize allowing the tympanic membrane to vibrate freely (Alberti, 2004).
- **Cochlea** – Found in the inner ear, the cochlea contains the necessary nerves to convert vibrations into signals that are sent to the brain. (Alberti, 2004).

Incoming sounds travel from the outer ear to the middle ear, and finally, to the inner ear to be converted into electrical impulses (Rochester Medical Center, 2019). Sound waves travel down the external auditory canal and strike the tympanic membrane. Vibrations from the tympanic membrane are passed to the ossicles, which amplify vibrations into the inner ear and into the cochlea. The inner ear then converts the vibrations into electrical impulses. The auditory nerve sends these impulses into the brain to be interpreted as sound. More information regarding the biology and structure of the ear can be found in Appendix M.

2.2.1 Ossicles

The middle ear contains three bones known as the ossicles. As shown in Figure 2.2, the ossicles are extremely small in size compared to other bones within the human body. The ossicles within the middle ear are only about 5 millimeters in length (Dobrev & Pfiffner, 2017, p. 7).

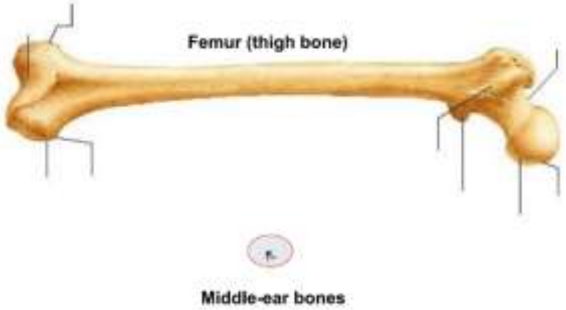


Figure 2.2: Comparison of middle ear bones to a human femur.

(Source: Dobrev & Pfiffner, 2017, p. 6)

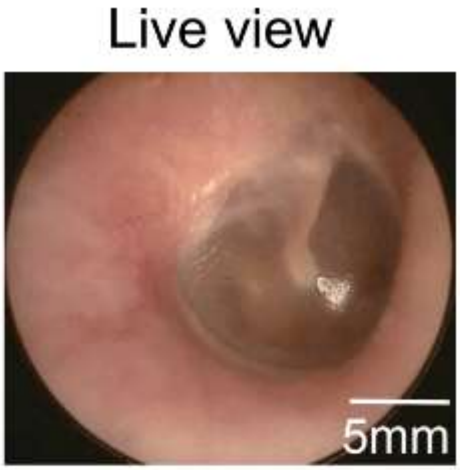


Figure 2.3: Live view of the middle ear. (Source: Dobrev & Pfiffner, 2017, p. 7)

The ossicles are distinct in shape and are connected to other structures within the middle ear. As shown in Figure 2.4, the malleus is attached to the tympanic membrane (Britannica, 2011). This attachment allows for the malleus to react with the tympanic membrane's movement caused by sound waves and frequency. The ossicles are connected by joints which affect the functionality of hearing (Britannica, 2011). Both the malleus and incus are attached by a synovial joint called the malleus-incus joint, or the incudomalleolar joint. This joint's function is to transfer the vibrational pressure between the ossicles. When the eardrum begins to move inward, the vibration is then transmitted to the malleus. The stapes is connected at the end of the incus and tympanic cavity.

Within the middle ear, there are many connective tissues that hold the ossicles together. These ligaments and muscles aid the ossicles in their movement as a response to external stimuli (Britannica, 2011). The posterior ligament of the incus is a fibrous band that connects to the posterior wall of the middle ear chamber. Along with the anterior ligament of the malleus, these two ligaments form the pivotal axis that the ossicles rotate about, conveying vibrations to the oval window of the inner ear. Further, the stapedius muscle stabilizes the vibrations of the stapes as it pulls on the neck of the bone. This muscle limits any unnecessary movement of the stapes, thus controlling the sound wave amplitude from the external environment to the inner ear.

The annular stapedial ligament is a ring of fibrous tissue that connects the base of the stapes to the oval window (Britannica, 2011). Flexibility and movement of this ligament is most important as it hardens and becomes fixated, it leads to otosclerosis.

There are three ligaments that keep the malleus attached to the middle ear: the anterior, lateral, and superior ligaments (Britannica, 2011). The anterior ligament is a fibrous band that goes along the top of the malleus to the anterior wall of the tympanic cavity. The lateral ligament is a triangular fibrous band that extends diagonally from the posterior of the tympanic notch to the head/neck of the malleus. The superior ligament is a fibrous band that extends from the roof of the tympanic cavity to the head of the malleus.

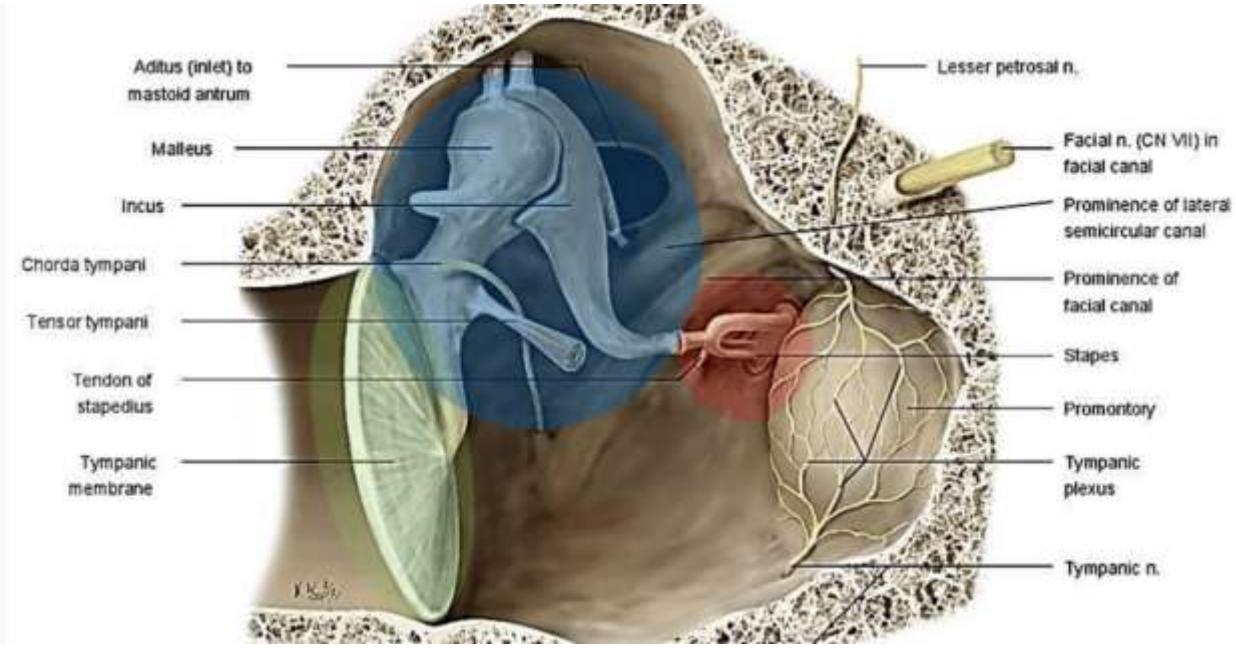


Figure 2.4: Anatomy of the middle ear. (Source: Dobrev & Pfiffner, 2017, p. 4)

2.2.2 Movement of the Ossicles

The movement of the ossicles is critical for effective hearing. The motion of the ossicles is generally proportional to frequency. At lower frequencies, such as 0.5 kHz, the malleus and incus move together in the same direction. However, at higher frequencies of 5 kHz the ossicles begin to move less uniformly and not in unison (Dobrev & Pfiffner, 2017, p. 39). This change in movement is due to the axis of rotation of the ossicles compared to frequency. As shown below in Figure 2.5, the axis of rotation changes in response to frequency (Dobrev & Pfiffner, 2017, p. 40). Within Figure 2.5, the motion of the malleus incus complex (MIC) is shown around the axis of rotation. The red areas represent significant movement. Blue areas and the dashed lines denote the axis of rotation where little to no movement occurs. The importance between varying frequencies and the ossicles is important to model as the movement of between the incus and malleus is not yet fully understood.

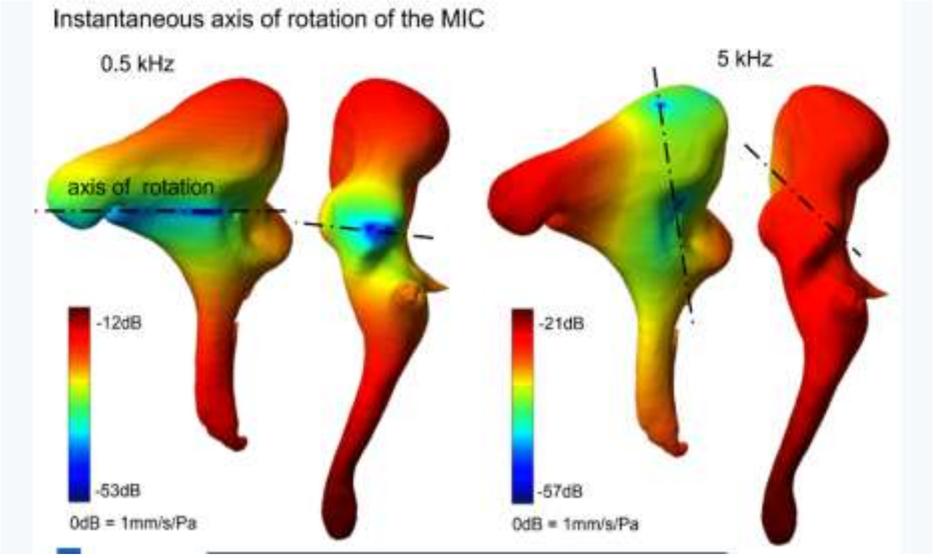


Figure 2.5: Axis of rotation of the ossicles at various frequencies.

(Source: Dobrev & Pfiffner, 2017, p. 40)

2.2.3 Variability within the Ossicles

The ossicles have anatomical variability which means the size and shape of the bones are not always identical between all people (Dobrev & Pfiffner, 2017, p. 10). For example, the size of the ossicles varies with age and species, as shown in Figure 2.6 below. The ossicles' variation is important to understand for research and surgical purposes.

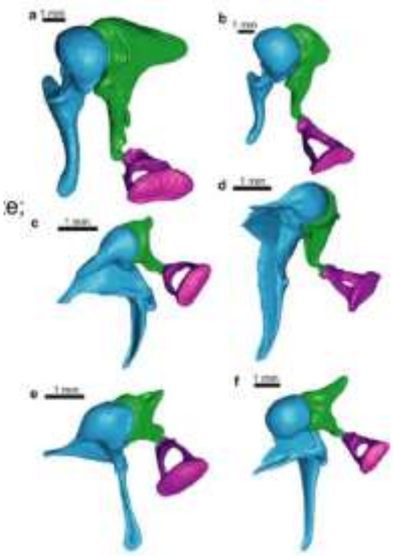


Figure 2.6: Various sizes of the ossicles based on age and species. A and B represent humans of different age and body size. C is the ossicles of a rat. D is the ossicles of a rabbit. E is the ossicles of a gerbil. F is the ossicles of a cat.

(Source: Dobrev & Pfiffner, 2017, p. 10)

2.2.4 The Dysfunctional Ear

For the middle ear to be effective, the ossicles must always be connected to transmit sound properly (NIDCD, 2013). If separated or fused together by a disease or infection, the ossicles have reduced functionality, which leads to hearing loss. Functionality changes when the ossicles become stiff and fixed to the skull or inner ear. As a result, vibration of the ossicles is hindered, which leads to a dysfunction in sound conduction. An example would be otosclerosis, which causes irregular growth of the ossicles within the middle ear. When irregular growth occurs, the stapes becomes fixed in place and does not allow proper vibration. Therefore, sound waves cannot be transmitted properly through the middle ear. Dysfunction of the ossicles can occur due to age related ailments and genetic disorders.

2.3 Sound Waves

Sound waves propagate through the air by the vibrations that occur in air pressure from external stimuli (Rossing & Fletcher, 2004). Vibrations enable the particles of surrounding material to have kinetic energy, which creates compression and rarefactions (Sound and Sound Waves, 2001). Compressions and rarefactions are propagation disturbances caused by differences in the medium's average density. Further, compression is the positive difference while rarefactions is the negative difference. These disturbances are directly correlated with sound intensity based on how many cycles take place (Davidovits, 2007, p. 163). From the compressions and rarefactions, a longitudinal sound wave travels from the vibration through a medium. Figure 2.7 shows how sound waves travel away from the source object. These waves travel in any area that has mass and elasticity. Figure 2.8 shows soundwaves produced by a tuning fork and their corresponding rarefactions and compressions. As sound waves travel, the distribution of the waves is identical through the air. Additionally, sound waves accelerate through an area at various speeds based on the conditions surrounding the waves. Three factors that affect the speed of sound are the temperature of the area it is traveling through, the object's density, and its elasticity. Sound waves travel slower in lower temperature and more quickly in higher temperature areas. If sound waves face the challenge of propagating between two different materials, the waves travel through the least dense material faster. Waves travel faster through mediums with higher elastic properties.

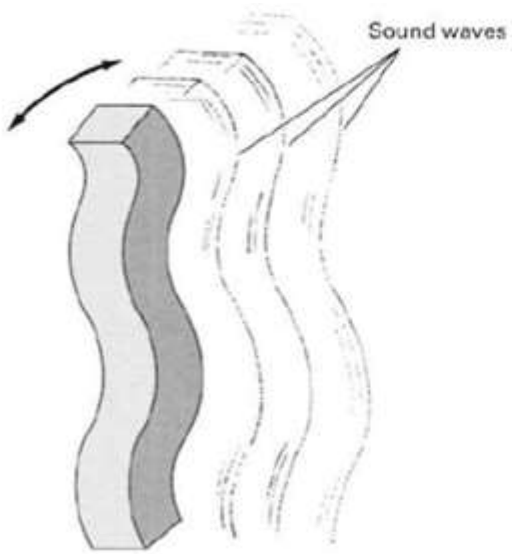


Figure 2.7: Vibration of an object to create sound waves.

(Source: Davidovits, 2007, p. 163)

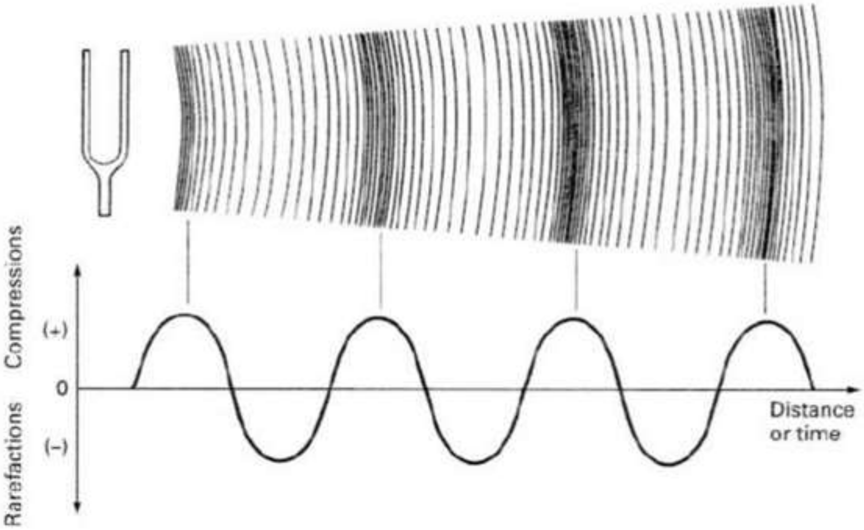


Figure 2.8: Soundwave produced by a struck tuning fork. (Source: Davidovits, 2007, p. 164)

Sound is represented through mechanical longitudinal waves that possess an amplitude, frequency, wavelength, and period (Sound and Sound Waves, 2001). The amplitude of a sound wave shows the volume as the height of the wave from the horizontal axis. If the amplitude is larger, then it has more energy and higher volume. Smaller amplitude leads to less intense volume of sound. Figure 2.9 shows soundwaves with varying amplitude. Frequency is the number of waves per second and as the frequency increases, so does the pitch. Lower pitches are a result of lower frequencies. Further, wavelength assists frequency in the determination of sound pitches. Wavelength and frequency have an inverse relationship in creating the sound one can hear. The relationship between sound wave speed (v), frequency (f), and wavelength (λ) is $v = \lambda f$ (Davidovits, 2007, p.164). However, the waves that combine are either in phase, meaning the corresponding or inverse amplitudes occur at the same time, or out of phase, and the corresponding amplitudes have a time delay. When in phase, sound waves combine and the sound becomes louder, when out of phase, the sound is quieter. Figure 2.10 shows destructive interference of soundwaves.

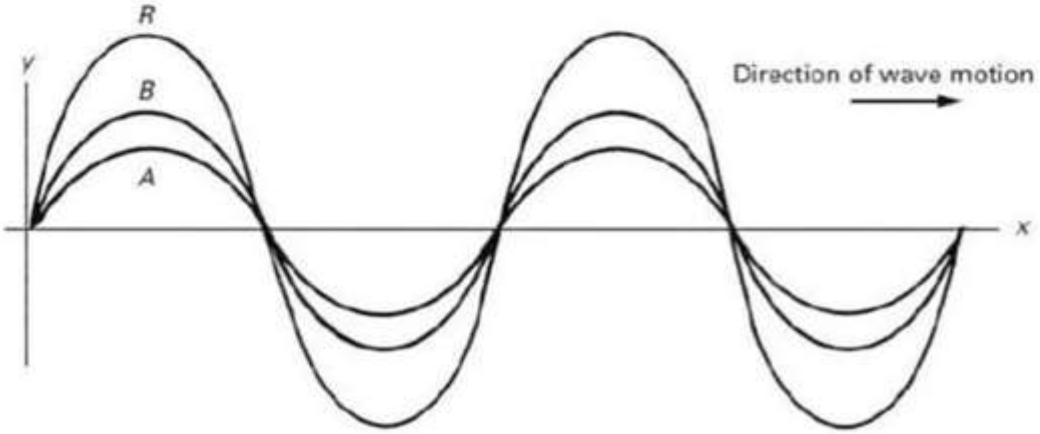


Figure 2.9: Sound waves in phase with each other creating a constructive sound.

(Source: Davidovits, 2007, p. 167)

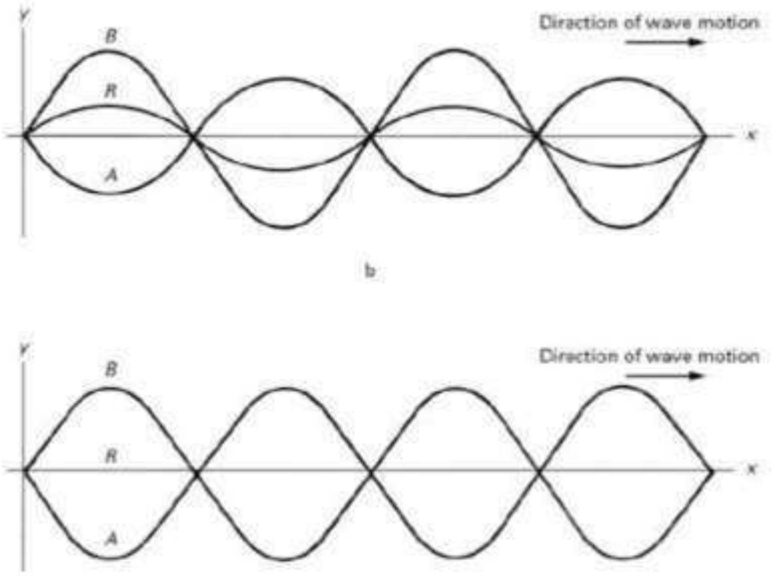


Figure 2.10: Sound waves out of phase with each other creating a destructive sound.

(Source: Davidovits, 2007, p. 167)

2.3.1 Sound Waves & Human Hearing

In order to hear, nerves within the inner ear that are sensitive to vibrations from sound waves must be excited by movement through the ear canal (Davidovits, 2007). Despite the human ear's complexities, it can only hear within a narrow range of sound frequencies. Human ears can only detect a range of frequency of 20 to 20,000 hertz. However, there are still variations on a person-to-person basis for detectible frequencies. Most human ears have primary sensitivity to frequencies between 200 and about 4000 hertz, and some ears are unable to detect frequencies over 8000 hertz.

2.5 Models within Otology Education

Otology is generally taught with outdated teaching methods (Nogueira & Cruz, 2010). The widely accepted and used otological models are static biology teaching models. These models are similar to models that high school teachers use within their classrooms. Some ear models are a simple “puzzle piece model”, which can be taken apart to look at in detail. However, it is an inactive model that is incapable of accurately demonstrating the true movements of an ear in response to sound and external stimuli.

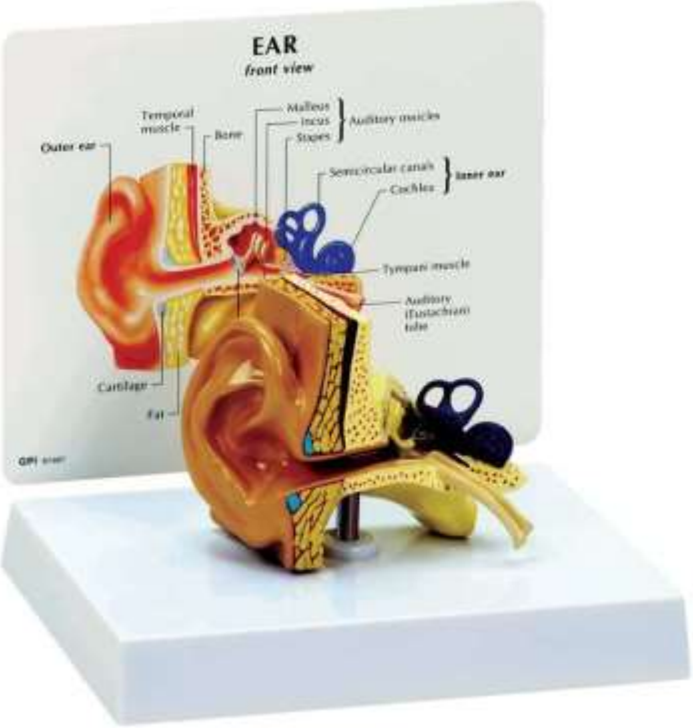


Figure 2.11: Plastic static model of ear. (Source: Fisher Scientific, 2019)

Figure 2.11 represents models that are currently used within otology education. These models represent a life-sized ear with all of the idealized anatomy shown (Nogueira & Cruz, 2010). The disadvantages with these models is that they are immovable and do not accurately present the movement of the sound waves traveling through the middle and inner ear. Additionally, the complex movement of the ossicles is not able to be shown in these models.

Recently, there have been attempts to make a successful and accurate demonstration model that is able to mimic the real effects of sound waves on the ear (Nogueira & Cruz, 2010).

However, surgical simulators and virtual reality screens are the closest any model has come to depicting accurate hearing mechanics. These models are focused on teaching surgeons rather than showing the physics and movement of the ear in response to soundwaves (Javia, 2012). These simulators are designed to be used for model procedures such as otoscopy and temporal bone dissection.

Otology has seen many developments in the use of surgical simulators for teaching and training (Nogueira & Cruz, 2010). One example is an advanced Japanese model used for teaching otoscopy. This model provides training with numerous concepts such as tympanic membrane perforation, cholesteatoma, sinuous outer ear canals, and tympanic glomus. As shown in Figure 2.12 it has a fixed unit, composed of an outer ear canal and middle ear that can be exchanged and examined indefinitely, along with a mobile head. Although this model is detailed and accurate, it is not available outside of Japan.

There are also other virtual simulated surgical models focused on temporal bone dissection (O'Leary, 2008). These simulators offer dissection with a wide variety of drills and tools, based on virtual reality concepts and direct interaction mechanisms with users, such as forced feedback. Since the 1990s, digital software for temporal bone dissection has been developed for use with success in medical residency programs in many countries, primarily being led by the United States and Germany.

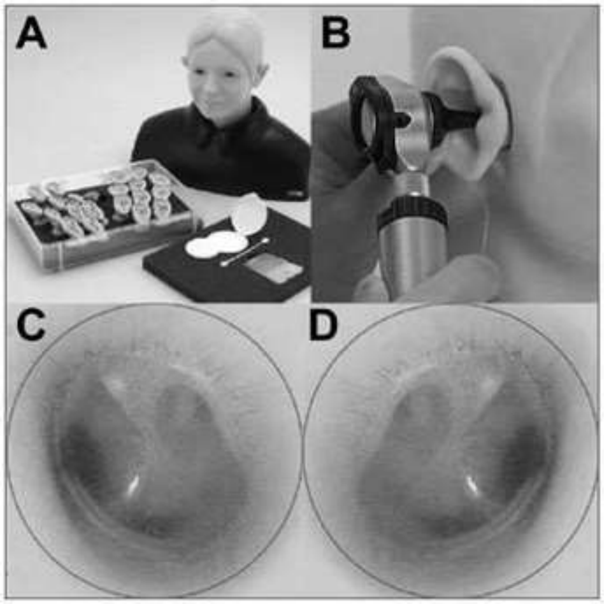


Figure 2.12: Otoscopy teaching and training model. A: model with head and several mobile parts for many disease types and otoscopy. B: practicing otoscopy in a model. C: Example of a normal otoscopy of a left tympanic membrane in a model. D: Example of a normal otoscopy of a right tympanic membrane in a model. (Source: Nogueira, 2010, p. 107)

Figure 2.13: Virtual Stimulation of the middle ear. (Source: Nogueira, 2010 p.107)

Figure 2.13 presents a North American simulator of the temporal bone being validated. The simulator is being used at various institutions with promising features (O’Leary, 2008). This tool provides features such as structure recognition and alarms when the trainee is close to sensitive anatomical landmarks. In addition, it also features 3D graphic rendering to simulate various temporal bone textures and consistencies. Another unique simulator is being developed in Germany and is available online for free download (Nogueira & Cruz, 2010). This software scores dissections from 0 to 10 according to whether important anatomical structures such as dura-mater in the middle fossa, the ossicles, the facial nerve, and the semicircular canals are preserved (see Fig. 2.14).

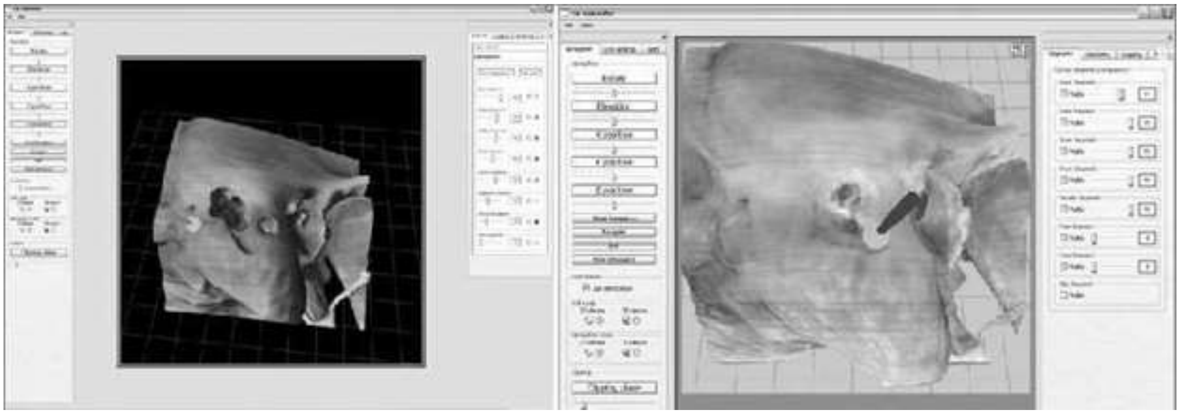


Figure 2.14. Digital screening of virtual dissection. (Source: Nogueira, 2010, p.107)

The benefit of virtual simulations have been shown in other specialties, including acquiring knowledge of anatomy (Nogueira & Cruz, 2010). Repeatedly, it has been reported that intensive training with virtual simulators helps decrease surgical time and complications.

Otology teaching models continuously have been moving to become more accurate and generally available. With the increased popularity of 3D printers, a new pathway to creating otological models has opened (Kuru, 2016). Although most of the current use of 3D printed otological models has been used for surgery, the flexibility of these machines allows for their potential use in a variety of applications, including the potential for creating models to show the physics of otology (Ding, 2019).

However, none of these models show how sound waves are perceived by the ear and transferred throughout the sensory organ. This lack of motion regarding key ear functions renders less effective when teaching the physics of otology.

2.5.1 Digital Models

Otological middle ear teaching models have been developed but are still lacking interactivity (Buytaert, 2011). One example would be a realistic computer model that was created by a research team at the University of Antwerp.

The model was created from Micro-CT scans that were used as geometric data for the modeling of the ossicles (Buytaert, 2011). This process faced initial difficulty due to low X-ray absorption of soft tissue. Resulting images were of such poor quality that they could not be used in developing a model. The team attempted to resolve this issue by using histological sections as data for 3D models, in order to present the soft tissue in high in-plane resolution. However, this method posed the issue of being destructive in nature as well as extremely difficult and time consuming.

The team also did research on morphological models in order to find ways to improve their digital models (Buytaert, 2011). However, the morphological models were either incomplete or low in resolution. In addition, many of these models had the suspensory ligaments omitted, resulting in inadequate presentation of important ossicular details.

Finally, the team attempted to improve realism by using orthogonal-plane fluorescence optical-sectioning (OPFOS) microscopy or tomography. This method improved imaging of both bone and soft tissue in high resolution (Buytaert, 2011).

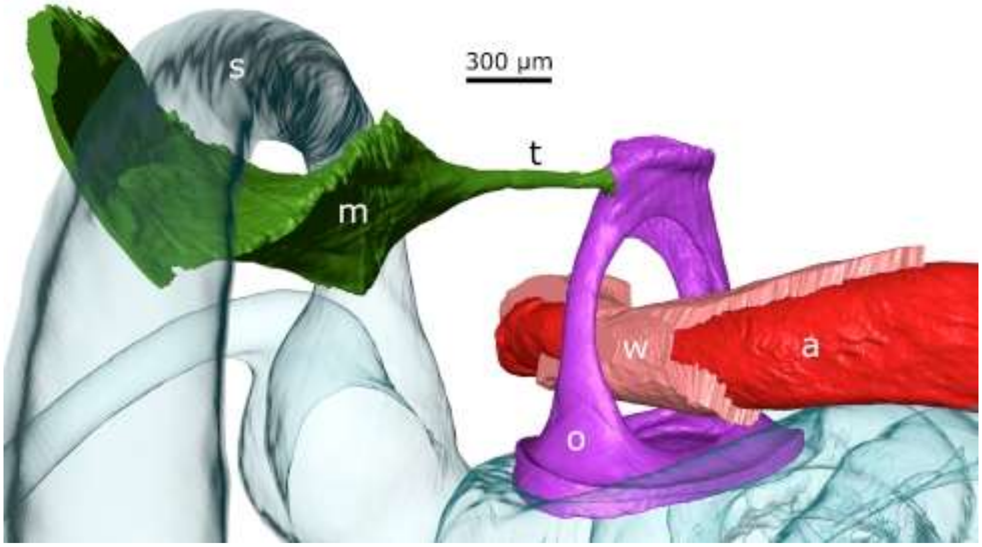


Figure 2.15: Close up of University of Antwerp model. (Source Buytaert, J. A, 2011)

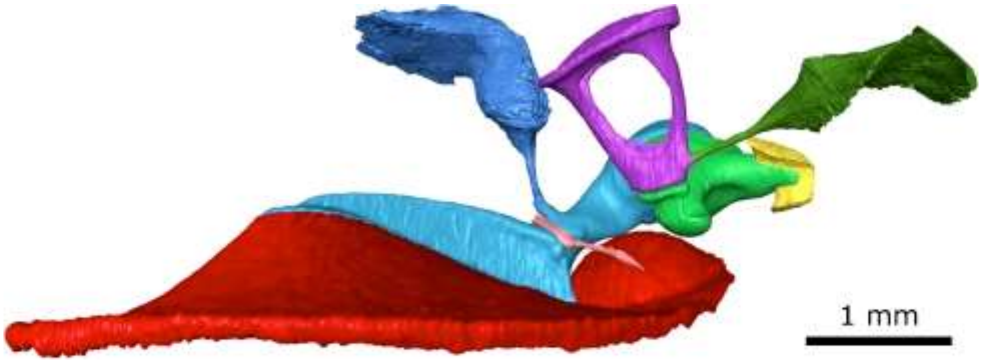


Figure 2.16: Overall view of University of Antwerp model. (Source Buytaert, J. A, 2011)

The University of Antwerp's model, as seen in Figures 2.15 and 2.16, is far more advanced, visually appealing, and high-resolution than previous models. Although it is capable of presenting the middle ear very clearly, as a digital model it provides a limited perspective of all parts of the model. Resulting in difficulty to grasp the model overall. However, its most significant shortfall is its inability to provide an in depth understanding of the middle ear's dense tissues, ligaments, movement, or functionality.

2.6 Learning Styles

Student learning styles vary greatly depending on many factors such as area of study, personality, and background. Learning styles are defined as, "...a distinctive and habitual manner of acquiring or imparting knowledge through study, experience or teaching" (Hill, Tomkinson, Hiley & Dobson, 2016, p. 123). Further, learning takes on many forms from memorization to analytical thinking and problem solving. Learning is the method by which students process, retain, and understand the information taught to them (Othman & Amiruddin, 2010).

Additionally, learning styles are multidimensional and possess components that are cognitive, affective, physiological, and psychological (Othman & Amiruddin, 2010). The cognitive aspect of learning is the process of analyzing, problem solving, making connections to outside knowledge, and recalling the concepts learned. On the other hand, the affective component is more personality and emotionally driven through one's awareness of the learning environment and how motivated one is to learn the material presented. Physiological components refer to using one's senses of sight, hearing, and touch to learn new concepts. Lastly, the psychological component of learning depends on one's sense of self and perceived strengths and weaknesses towards learning.

2.6.1 VARK Student Learning Model

The VARK model, or Visual, Aural, Reading, and Kinesthetic model, identifies the four main types of learners that students tend to be (Othman & Amiruddin, 2010). Previously, the VARK model was known as VAK until Fleming redefined the model through his research and studies in 2006. It is important to understand that students may identify with more than one learning style throughout their education.

The V in VARK represents a student who is a visual learner (Othman & Amiruddin, 2010). Visual learners tend to depend more on figures and graphs to display information on the subject. Further, demonstration is vital to a visual learner's understanding of key concepts.

Whether solving a math problem all the way through to hand drawing a graph from an equation, visuals such as pictures and graphs are not only critical in how visual learners learn but also in how they can explain concepts to their peers. Typically, about 29 percent of students are classified as visual learners within the classroom.

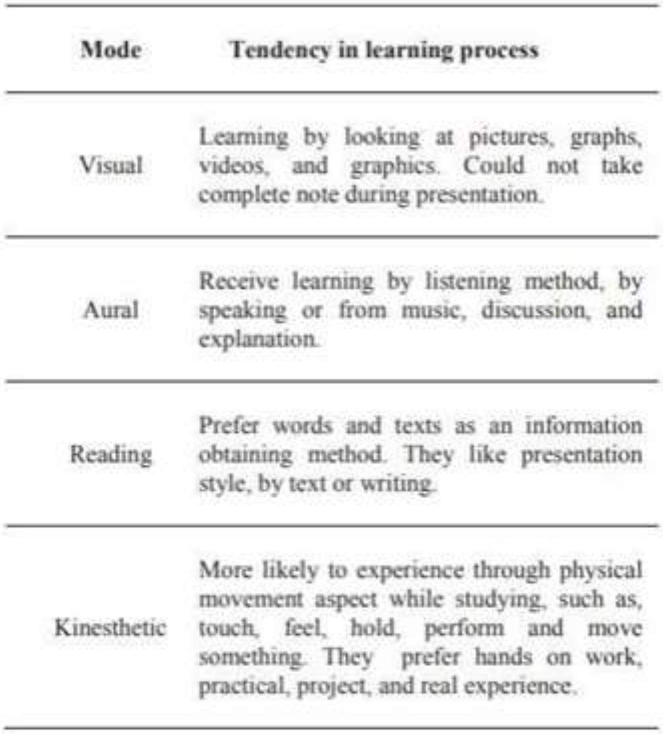
The A in VARK signifies an aural student learner (Othman & Amiruddin, 2010). Aural student learners are keener on learning using auditory strategies. These students rely on listening and interpreting a teacher's words instead of writing class notes or seeing images. Repetitive listening to recorded lectures and discussion with fellow students allow aural learners to solidify their learning. These learners tend to be more intuitive at learning new languages and writing.

The R in VARK refers to the learners who prefer to read about the subject they are studying (Othman & Amiruddin, 2010). These learners utilize textbooks, lecture notes, and other printed literature to achieve mastery of a subject. Students like these benefit from writing down their own notes during lectures to better retain the information being taught.

Students who represent the K component in VARK are kinesthetic learners, meaning they learn through experiences (Othman & Amiruddin, 2010). These learners particularly benefit from touch and are naturally more tactile. Usually, these learners excel in very physical sports due to their high energy and need for physical interaction with their environment.

Overall, the VARK model is able to identify four of the most common learners seen within classroom environments and address their strengths (Othman & Amiruddin, 2010). Models such as these benefit teaching professionals to be able to better educate a classroom of different types of learners. In Table 1, a summary of the types of VARK learning styles is shown.

Table 2.1. Types of learners. (Adapted from Othman, 2010, p. 652)



Mode	Tendency in learning process
Visual	Learning by looking at pictures, graphs, videos, and graphics. Could not take complete note during presentation.
Aural	Receive learning by listening method, by speaking or from music, discussion, and explanation.
Reading	Prefer words and texts as an information obtaining method. They like presentation style, by text or writing.
Kinesthetic	More likely to experience through physical movement aspect while studying, such as, touch, feel, hold, perform and move something. They prefer hands on work, practical, project, and real experience.

2.6.2 The Educational Method for Graduate Students

Educational methods for graduate student instruction usually falls into one of two main methods: seminars and lectures.

The seminar approach involves teaching through discussion (Casteel, K. 2007). This entails establishing learning goals for a seminar in which it is essential for the instructor to ensure the proper direction and context for the course. In addition, many believe that within this approach, the instructor should request the students to write a short intellectual autobiography. This method provides the instructor with what the student, “thinks and knows at the start of the experience" in order to best tailor the remainder of the course to achieve the desired learning goals (Halpern & Hakel, 2003, p. 39).

When dealing with graduate students, this is significant, as they have had time to develop set ideas and assumptions about the world. Halpern & Hakel (2003) suggest that instructors must take into consideration exactly how much information their students will need to recall when they attempt to transfer what they have learned to a new situation. By imagining the future use of the course content, instructors can more effectively guide their decisions about how deeply to probe a particular area or what level of detail is necessary.

When it comes to teaching, feedback plays a significant role (Steen, Bader, & Kubrin, 1999). One of the important factors that is often found missing, is the systematic and corrective feedback about the consequences of various actions. Without this, the students will not learn properly from any authentic learning task. Activities like simulations, role-playing, and case studies should be integrated into graduate-level courses to ensure students learn what they need to know. This means that active work is better than a simple lecture within a seminar.

Even though lectures are often used at the undergraduate level and into the graduate level, the lecture method is found to be ineffective for graduate level learning (Halpern & Hakel, 2003, p. 41). It does not foster any deep understanding of the material, or include the students in the academic discourse. Graduate students require cues to engage them in the material actively, which is not often present in lectures.

The active learning method fills in the gaps of the lecture method (Clarke, 2010). Within this method, the instructor is very communicative with the students. The course would immediately begin with either a core idea, a posed problem, or a group exercise.

This method takes serious advantage of class reviews (Clarke, 2010). At the end of the class, a short amount of time is taken to ask the students to summarize the ideas presented, solve a sample/similar problem, apply their knowledge to new information, or comment on the new information they have learned. This will allow the instructor to focus on the weaknesses of the students and find a different method to approach them with when teaching. Additionally, this teaching method often uses objects within presentations, with anything that can use hands-on learning should. Whether it be through the use of models, videos, or movement, the students should be actively involved in the instructor's lesson. This forces students to be active and alert with the information they are being taught.

2.7 The Otology Program at UniversitätsSpital Zürich

One of UniversitätsSpital Zürich's (USZ) areas of specialization is otorhinolaryngology (Swiss Health, 2019). The otorhinolaryngological department trains medical students and physicians' assistants using teaching methods and models.

The audience of the ENT department lectures varies greatly due to the difference in educational background of its students (University Hospital Zurich, 2019). Due to the specificity of this department there is a relatively large gap between the available acoustic teaching models and those that would be appropriate for the expectations of the program. The current teaching methods for the students entering this department mostly relies on lecture-based teaching with little to no interactive elements. An appropriate acoustic model for the program would need to feature moveable portions to illustrate the physical interactions within the ear (Nogueira & Cruz, 2010). Such a model would need to clearly depict the interaction of sound waves against the membrane of the ear and their transfer into the ossicles and finally into the inner ear. Additionally, such a model would need to show how a variety of medical conditions could affect the movements within the ear. As a result, the focus of their program lies on trying to find an alternative model that will accurately aid their teaching.

2.8 Summary

In this chapter we have presented a picture of the status of current otology education methods and models and the needs of the otology program at USZ. Otological methods and models have improved over the years through advancements in technology. Nevertheless, the educational models at USZ and elsewhere still need improvements to enhance graduate level education. In the next chapter, we will explain how we plan to identify better educational models and pedagogy for USZ's otology education programs.

3 Methodology

The goal of our project was to improve the educational understanding of the ear by developing a more effective middle ear model. This was achieved by identifying the shortfalls of current middle ear models and developing a more interactive, mechanical, and accurate model. The measurable objectives were:

- Determine the effectiveness of current teaching methods and models for the middle ear at UniversitätsSpital Zürich;
- Identify the shortfalls of current middle ear models that are important to students, professors, and physicians;
- Create and identify how to make a more mechanically and physically accurate middle ear model for improving the understanding of ear functions;

We used the methods described below to achieve all our objectives listed. A contact list was provided by Dr. Dobrev on potential interviewees. Our team reviewed the contacts' credentials to determine the most relevant experts. Post-interview follow up emails were sent to inquire about other potential contacts.

3.1 Effectiveness of Current Teaching Methods and Models

Our first primary objective was to determine the effectiveness of current teaching methods and models of the middle ear. In order to properly make recommendations, current educational methods were identified. In order to achieve this we conducted interviews with professors and graduate students and observed classroom teaching methods in practice.

3.1.1 Professor and Graduate Student Interviews

Our interview questions were formulated to understand the effectiveness of current teaching methods and models used within the classroom environment. Professors were interviewed to provide us with insight into the teaching models they have prior experience with and their teaching methods. We asked graduate students to provide us with their input on the effectiveness of digital teaching methods and their learning styles. The professors that we interviewed taught at UniversitätsSpital Zürich, University of Zürich, and Hochschule Reutlingen. All graduate students were selected from the Biomechanics of Hearing research group. In total we conducted formal interviews with six professors and two graduate students. All interview protocols can be found in Appendix C.

3.1.2 Individual Instruction for Increased Understanding

We attended lectures from Dr. Ivo Dobrev on hearing mechanics to increase our understanding of key topics, such as the anatomy and function of the inner and middle ear. Professor Blake Currier, a physics professor at WPI, reviewed basic physics concepts on oscillations and waves that relate to hearing with us. Both lectures helped us to improve interview questions overall. Further, the lectures helped us to create a more efficient model from our understanding of how frequency relates to the ossicles.

3.2 Shortfalls of Current Middle Ear Models

Our second objective involved identifying the shortfalls of current models and components of the middle ear that are desirable for incorporation in future models. We interviewed professors, students, researchers, and physicians to understand what could be improved in current otology models.

3.2.1 Professor, Postdoctoral Researchers, and Physician Interviews

A series of interviews were conducted to best determine shortcomings in current otological models. We asked professors to identify which part of the ear was least understood by students. Further, the questions also focused on the advantages and disadvantages of physical and digital models. Graduate students were interviewed to get a perspective on their experience with interactive models in the classroom environment. In addition, we asked about their academic background in physics and its effect on learning about hearing mechanics. Postdoctoral researchers and physicians were asked to identify the current gaps in hearing research. Early interviews were used to get an understanding of current otological models and their shortfalls. These early interviews allowed us to narrow down our focus to the middle ear. Using interviewee expertise, in later interviews, we asked more about the science behind how the ossicles move in relation to frequency. Our later interview questions allowed physicians to indicate components that could be improved in middle ear models. We interviewed a total of four postdoctoral researchers and two physicians. All postdoctoral researchers interviewed, performed bone conduction research concurrently in the Biomechanics of Hearing lab.

3.3 Identify and Create a More Accurate Model

The third objective was to create and identify how to make a more mechanically and physically accurate middle ear model. Our team created a model of the ossicles in relation to frequency. We wanted to maintain the anatomical accuracy of the middle ear, while also making it functionally realistic. An understanding of the technical components was required to make recommendations for improved teaching models of the middle ear. To achieve our objective, we learned to digitally isolate the ossicles with software, 3D print our model, and create a prototype. Additionally, we conducted interviews with a professor from a model simulation team in Korea and Phacon, a biomedical company. After we created our model, we requested feedback from professors and graduate students.

3.3.1 Professor, Researcher, Physician, and Biomedical Company Interviews

In order to best create our model, we interviewed professors, researchers, and physicians. We chose to interview these groups since they would most directly work with interactive models. The interview protocol for each interview had specialized questions based on the interviewee's expertise. We asked professors to explain which type of model they preferred and if they were comfortable implementing more interactive models into the classroom. Our questions for postdoctoral researchers were centered on technical aspects of creating the model such as Micro-CT scans, software, and 3D printing. Similarly, physicians were asked about the anatomy of the ear and ailments that can affect the ossicles.

Phacon was selected for an interview due to the advanced nature of their current otological surgical models. We interviewed Phacon to understand potential design challenges, model materials, and how they develop successful models. We interviewed the simulation research group in Korea due to their close work with our sponsor and cutting edge otological model development. Their research includes developing a personalized middle-ear finite element model based on Micro-CT images. This interview allowed us to explore existing simulated models in greater detail.

3.3.2 Creating Our Middle Ear Model

In order to produce our own demonstration model of the ear, we identified three key pieces of software to familiarize ourselves with: Amira (Thermo Fisher, 2018), Geomagic Design X (3D Systems, 2019), and SolidWorks (Dassault, 2019). Two of our group members already had sufficient experience with SolidWorks. All group members learned the basics of each of the software. Our sponsor's lab had these programs available for us to use. To familiarize ourselves with the programs, we used them to go through the process of isolating and modifying the stapes starting from a Micro-CT scan of the middle ear.

Amira is a, "…3D data visualization, analysis and modelling system" (Thermo Fisher, 2018). It allows the user to visually represent Micro-CT scans in 2D or 3D. Amira allows the user to isolate sections from a larger CT scan. We used Amira version 6.1.1 from 2016. Geomagic Design X is a, "…comprehensive reverse engineering software" that, "…combines history-based CAD with 3D scan data processing so you can create feature-based, editable solid models compatible with your existing CAD software" (3D Systems, 2019). The user can easily convert 3D scan data into CAD models with modifiable features. Our team used version 5.1.0.0 of Geomagic Design X, which was released in 2014. SolidWorks allows, "You to conceptualize, create, validate, communicate, manage, and transform your innovative ideas into great product designs" (Dassault, 2019). Through SolidWorks Premium 2018 x64 Edition we were able to modify the features of our 3D models.

From familiarizing ourselves with these key pieces of software, our team worked to make an anatomically correct model of the middle ear. First, our team imported Micro-CT scan data into Amira. Amira displays the density data as voxels, or volumetric pixels. Then, we constrained the data, to only see bone, by moving the minimum viewable density viewable density value up to remove soft tissue and air. After modifying the constraints, we visually identified the stapes and selected it. We selected it by going through 2D slices of data and highlighting the desired ossicle. Amira's integrated interpolation feature was used to speedup this process in repetitive areas. After the stapes was completely selected, we looked at it in 3D space to inspect for errors. We went back to delete any floating points or inaccuracies. Lastly, we exported the data as an STL file to move into Geomagic Design X.

In Geomagic Design X we prepared the file by filling holes, smoothing out layers, and removing soft tissue. We first had to turn the voxels from the data from Amira into surfaces in Geomagic. The initial model that we imported had unnatural holes and was layered from inaccurate interpolation. There were areas with soft tissue because when we initially constrained the density values in Amira some harder tissue made it into the range. Many functions of Geomagic were used for this process, including the Smart Brush tool to smooth out the surface of the stapes to make it more favorable to 3D printing. When we finished preparing the stapes, we exported as an STL for importing into SolidWorks.

In SolidWorks we oriented the three individual bones into the position of their real anatomy, using the stapes that we isolated and two files for the malleus and incus provided by our sponsor. We put them into an assembly to show how they would come together after the parts were 3D printed. We also scaled the model up by 20 times to make it big enough to be held by hand but small enough to show how vibration travels through it.

3.3.3 Additive Manufacturing

To 3D print the three ossicles we chose the company Teil3. The company could produce an accurate print with minimal lead time, while giving us the colors we wanted. We chose to print the malleus, incus, and stapes in three different colors, red, blue, and green, respectively. The color difference allows one to easily point out each ossicle to students in a classroom setting. Since we printed at a scale of 20 to 1, the longest dimension on any of the parts was 17.5 cm, within the range of most standard 3D printers.

3.3.4 Prototyping

After 3D printing the ossicles, we designed and prototyped a way to connect them to each other and a support structure. To simulate the joint between the malleus and incus and the joint between the incus and stapes we used elastic bands. First, we embedded helicoils into the plastic using a soldering iron. Then, we tightened screws into the helicoils. Finally, we tied three elastic bands to the screws across each joint. In order to tighten the elastic bands accurately across a joint, we looped them two to three times. The placement, orientation, and tension of the bands depended on accurately representing the range of motion of the ossicles.

We created the support structure to hold the model and to show where the ligaments and muscles connect to the bones. We made the structure out of 80/20 Inc. 20 Series T-slot. Our team glued Velcro to the areas where ligaments and muscles attach to the ossicles from the outer structure of the ear. The model is completely removable from the structure allowing one to manipulate the model either inside or outside the structure.

3.3.5 Model Feedback

In order to identify methods to improve our model, we created an interview protocol for professors, which can be found in Appendix C. We created these questions to identify if professors would utilize the model within their classrooms. Additionally, we utilized this interview protocol to gather feedback on potential improvements for our model in the future.

At the conclusion of the project we conducted informal interviews with members of the Biomechanics of Hearing research group regarding their thoughts on the effectiveness of our model. These interviews with both graduate students and professors provided us with important feedback on the usefulness of our model. We used this feedback, in part with our other research and interviews, to create our recommendations for future enhancements of our model.

3.4 Summary

Overall, our methodology worked to achieve the objectives of determining the effectiveness of teaching methods, identifying shortfalls of current ear models, and the components desired to be seen in our middle ear model. We achieved our objectives through interviews, lectures, and model creation. From these methods, data was collected from graduate students, professors, postdoctoral researchers, physicians, a biomedical company, and an external lab in order to provide a coherent list of suggested improvements to the quality of middle ear models. The following chapter presents the results we obtained with an analysis of our data that allowed our team to arrive at our conclusions and recommendations.

4 Results and Analysis

The goal of our project was to improve the educational understanding of the ear by developing a more interactive middle ear model. Our objectives for this project were to determine the effectiveness of teaching methods and models within otology, to identify shortcomings of current middle ear models, and to identify how to create a more mechanically accurate model of the middle ear. This section is comprised of our team's findings in relation to our objectives for the project and how we achieved our goal through our results.

4.1 Effectiveness of Current Teaching Methods and Models

In this section, we present our findings on the current teaching methods used within otology and limitations of middle ear models.

Finding #1: The current teaching methods used within university courses rarely include interactive models.

In all our interviews with professors, it was mentioned that the use of interactive teaching models within the classroom is minimal. Interviewee in Appendix D expressed concerns about interactive models utilizing too much class time. However, we learned through the five professor interviews that we conducted out that all were open to implementing more models within their lectures whether they be a digital or physical model. The two graduate students we interviewed both mentioned the integration of technology within the classroom environment. Both mentioned the use of PowerPoint slides being the primary mechanism to relay classroom concepts and information. The two graduate students also noted that models were rarely used within their undergraduate and graduate courses. They expressed that an interactive model would have been more beneficial in solidifying their understanding of key concepts within a course.

There are four learning styles students can have: visual, aural, reading, and kinesthetic. In addition to PowerPoint presentations, both physical and digital models would be very helpful in addressing all types of learners. Visual learners can utilize the digital model to observe anatomically changes based on external stimuli. Aural learners would have the opportunity to listen and see the model. Reading based learners already prefer presentation based teaching styles and could benefit from an interactive model. Kinesthetic learners would have the opportunity to manipulate the movement of the middle ear model to solidify concepts of hearing and anatomy.

Based on a review by our team of the current PowerPoint-based lectures used within the otolaryngology department at USZ, we noticed the occasional use of scans and videos to convey the physics behind hearing. However, there were no physical models available to help clarify the information taught to the students in the class. No interactive digital model was used within any presentation that could be manipulated to show how the ear functions when engaged in hearing sounds.

The absence of the use of any models in lectures was an important discovery as it illustrated the importance of moving forward to create an interactive physical or digital model.

Finding #2: University Hospital of Zürich provides an ineffective physics review for middle ear lectures.

From lectures with Dr. Dobrev, we found that the lectures the ENT department uses to teach about the middle ear include an overview of physics definitions. However, the review of definitions requires significant class time and cannot be easily reviewed within the lecture. Therefore, a quick reference guide provided by the department would be helpful. Since these lectures are typically a week or two out of the year, the lectures do not use textbooks to supplement student learning. A reference guide would allow students to have the opportunity to review these concepts independently of class time, if needed. Additionally, this sheet would reduce the time lecturers have to spend on reiterating physics definitions in the beginning of the course.

Further, within the lectures there are no visuals portraying physics concepts alongside definitions. There are many physics websites that provide a basic insight into how soundwaves propagate through a medium and how the human ear perceives them. For example, PhET, a science website run by University of Colorado Boulder, has a wave interference simulator that would provide a visual and more interactive way to convey basic wave principles. These websites are extremely beneficial for showing the most basic physics concepts such as sound waves and interference. However, these website's limitation lies in their inability to portray basic physics in relation to how the middle ear functions.

4.2 Shortfalls of Current Middle Ear Models

In this section, we present our findings on the shortfalls of current middle ear models and structures that are most important to be modeled for students, research professors, and physicians to improve otology education.

Finding #3: The models currently available for otology education do not represent hearing mechanics.

Through our interviews with professors who have done research on hearing mechanics, our team agreed that the current static models available only depict the idealized anatomy of the ear. The overwhelming response from professors was that models need to be improved by showing the physics behind hearing. Professors mentioned that despite researchers not understanding the entirety of hearing mechanics, displaying what is known is still an important advance in the field of otology education.

From interviews with physicians, we found that by only having models that depict the ear’s anatomy, medical students do not properly understand the movement caused by soundwaves in the middle and inner ear. In turn, this affects their ability to diagnose and understand diseases and infections that affect the middle ear.

The significance of this finding from researchers and physicians demonstrated the need to show how the middle ear operates with regards to physics concepts.

Finding #4: The ossicles are the most desired structure to be modeled.

Most interviews with students, professors, and physicians revealed the ossicles to be of the utmost importance to model. Dr. Röösli, an ENT surgeon from USZ, insisted the ossicles were significant due to their complexity and how important these three small bones are to hearing. By having a functional model of the ossicles, Dr. Röösli felt lectures could not only give ideas about the movement of the bones but also provide greater detail.

Dr. Ivo Dobrev of USZ has confirmed that the ossicles still hold mysteries to researchers and physicians alike. However, the significance lies in what we can show even if a scientific theory has to confirm how they operate.

This was a crucial discovery as it allowed our team to identify which component of the middle ear to model and how much of an impact it could make in the field of otology.

4.3 Identify and Create a More Accurate Middle Ear Model

In this section, our team will present our findings on how to create a better mechanical and physically accurate model of the middle ear to supersede static models’ current limitations.

Finding #5: Mobility is important for a model of the ossicles.

Based on our interview with Prof. Dr. Med. Alex Huber, we learned that mobility in a model of the ossicles is very important. Dr. Huber explained that how ossicles move is directly correlated to the frequency of sound waves in a healthy ear. This concept is not fully understood, but it is an effective method to show how the principles of physics relate to hearing.

From Dr. Dobrev, we learned that the ossicles do not move uniformly at every frequency. The axis of rotation on both ossicles changes as the frequency increases. Instead of the ossicles moving uniformly together, both bones move in opposite directions. The ossicles generally have constant movement around an axis of rotation. However, the movement of these bones' changes in response to higher frequencies. The uniformity of the movement becomes nearly nonexistent at higher frequencies. As frequency increases, the axis of rotation involving these structures changes. Despite the knowledge of this phenomenon, there is no clear reasoning behind why it occurs.

These findings were significant as they identified the frequency based movements of the ossicles that needed to be modeled.

Finding #6: Variability and conditions the ossicles could be affected by is important to model.

All our interviews with physicians and researchers confirmed that current models of the ear are idealized and give no regard to anatomical variation. Anatomical variation is the difference in anatomy that exists from person to person. Physicians stated that the importance of anatomical variation becomes critical for surgeons who must operate on these small ear bones. The physicians felt that by showing variability in the middle ear, medical students could have another method to be exposed to differences in human ears without having to perform dissections.

One of the graduate students interviewed, Merlin Schär, had a dual background in medicine and engineering. Merlin provided insight into the medical courses he took to become a medical doctor and classes related to his Ph.D. in bone conduction. He noticed that the only variation in anatomy shown to him in his time at medical school was during the gross anatomy section. Therefore, as a student Merlin felt that showing the variability in human anatomy would create a well-rounded model and aid learning among students who previously did not have a medical doctor background.

Additionally, across all our interviews the importance of depicting a dysfunctional ear was just as important as showing a functional one. The modeling of a dysfunctional ear allows for a better understanding of what to look for when diagnosing, treating, and researching the middle ear. Through our interviews and the lectures that we attended we learned how the joints that connect the ossicles swell in response to infection. By swelling up, the joints becomes stiff and in turn negatively impact hearing. A model of these various conditions could help physicians understand the effects of these ailments to diagnose and treat patients more effectively.

These findings were extremely valuable to us as they influence how we would need to create the joints between the ossicles and the variability in the form of the ossicle.

Finding #7: Software and 3D printing can be utilized to create an interactive ossicles model

Based on our findings from interviews with professors, students, and physicians, we decided upon creating a physical model that provides mobility of the ossicles. An interactive physical model would be able to satisfy all types of learners within a classroom or research environment. Therefore, we decided to utilize computer software and the use of rapid prototyping to create our model of the ossicles.

In his interview, Merlin mentioned the usefulness of the computer program Amira to create an interactive model. Using Amira, we could use already available Micro-CT scans to isolate anatomy. Through the observation of Merlin and Dr. Dobrev we learned how to identify the ossicles in Amira using Micro-CT scans. Additionally, these observations provided the instruction on how to have our model ready for 3D printing.

We learned from an interview with Phacon's Managing Director, Robert Hasse, that Phacon utilizes similar methods to create their temporal bone simulation models. Their methods include rapid prototyping, material selection, and customer feedback to further improve their models. This interview reinforced our decision to 3D print the model as it was similar to biomedical companies' modeling processes. From this interview, we thought about what materials could be used to better represent the bones and flexibility of the ossicles. However, due to time and resource constraints we decided to use the basic plastic option known as PLA. Our team realized rapid prototyping would be beneficial to our model, so a SolidWorks model was created. The SolidWorks model provided a digital representation of the ossicles but also allowed us to include areas where screws could be placed in the design.

From our interviews and analysis of current anatomical models, our team decided to color code the ossicles to make the anatomy more identifiable. Therefore, students would be able to more easily identify the three bones and clearly see the unique shape of the ossicles.

The findings were extremely valuable in the creation of our interactive model to improve otology education.

Finding #8: The model we created can be used to show the functionality of the ossicles in relation to frequency.

Based on our research we created a model of the ossicles. Our model allows for movement of the ossicles in relation to various frequencies. As shown in Figure 4.1, our model has elastic bands supported by screws affixed to the ossicles by embedded helicoils to mimic the joints between the ossicles. The screw placement was based upon the axis of rotation of the ossicles to ensure accuracy of movement when manipulated. Elastic bands of varying sizes were used to control the tension of each joint.

Figure 4.1: Our model of the ossicles at different angles.

Because of the screw placement and elastic bands used, our model can mimic the movement of the ossicles from low to high frequencies. Our model was scaled up by a factor of twenty to allow for easy movement of the ossicles by hand. Each ossicle is a different color for easy identification of which part of the model is moving and being shown.

Additionally, we created a support structure for our model to represent the temporal bone that the ossicles are within, as shown in Figure 4.2. The ossicles are connected to the temporal bone through muscles and ligaments, which we simulated using Velcro connections. We wanted the ossicles to be detachable from the support structure in order to be passed around a classroom and to be manipulated by hand.

Figure 4.2: Our model of the ossicles enclosed within the support structure.

Finding #9: The model we created has the potential to become an advanced teaching tool

Based on an interview with Vartan Kurtcuoglu, Professor of Physiology at the University of Zürich, we found that the model we created has the potential to become an advanced teaching tool. Professor Kurtcuoglu specializes in computational and experimental models of fluid dynamics and the human body at the University of Zürich. He mentioned that despite computational models having more advantages, most students respond to and benefit more from physical models. Currently, our model would be most useful for students who have limited background in otology or to show how sound waves affect the middle ear. Professor Kurtcuoglu felt the color coding was unnecessary for upper level students who already know the structures. Additionally, he noted that the scaling our team used was appropriate for showing how the ossicles move in relation to frequency and a slightly smaller scale might be better to show the interaction between ossicles. However, the accuracy of the anatomy and minute movements are unable to be shown at the scale we currently have for the model. Despite these potential limitations, Professor Kurtcuoglu acknowledged that the model we have developed is more advanced in terms of how the ossicles are connected than the current physical models he utilizes within his classroom.

From discussions with Dr. Ivo Dobrev, as well as professors and graduate students in the Biomechanics of Hearing lab, we learned of ways our model could be improved. First, they suggested demonstrating where the model's location fits in with the rest of the ear. This would help students who are less familiar with the anatomy and orientation of the middle ear. Second, since the model has the ability to show vibrations through the middle ear, it would be beneficial to show how that vibration is transferred from the stapes to the inner ear. Additionally, graduate students felt color coding the ossicles could be beneficial for less experienced students, however for themselves it was unnecessary.

From these findings, our team was able to understand the shortcomings of our own model and what could be improved in the future. Our model, with modifications, has the potential to become an advanced teaching tool. To do so, for more advanced audiences, adjustments must be made to scale the model appropriately to the anatomy, have more accurate joints, and forgo the coloring of the ossicles.

4.4 Summary

From our findings, our team was able to create thoughtful recommendations. Our team decided that focusing on creating a model of the ossicles and their movement in response to frequency was most valuable. Our team's recommendations and conclusions are in the following chapter.

5 Conclusions and Recommendations

In order to further otology education, we created a physical model to display the movement of the ossicles in relation to the frequency of sound waves. In addition, we have created recommendations for potential model improvements for teaching otology at the UniversitätsSpital Zürich. We believe our recommendations will contribute to the field of otology and how the UniversitätsSpital Zürich is able to teach the relationship between hearing and the physics behind it. We list our recommendations in detail below.

5.1 Recommendations

I. These learning supplements should be used to give students a more accurate physics review for ENT lectures at UniversitätsSpital Zürich:

1. Physics Quick Reference Guide
2. Interactive Physics Websites
3. Interactive Physical Model of the Middle Ear

We recommend the ENT department at the UniversitätsSpital Zürich address and effectively implement a comprehensive physics review guide within their department courses to aid students with a limited physics background. The use of a physics reference guide and interactive websites would allow students easy and clear access to the concepts and definitions without compromising class time. Our proposed example of a physics reference guide with interactive websites can be found in Appendix B.

Further, we our interactive physical model be implemented within ENT lectures. UniversitätsSpital Zürich should give a survey after lectures to students to determine if the reference guide and websites added educational value.

II. UniversitätsSpital Zürich should focus on the ossicles and their mobility when creating models for the middle ear.

We recommend that the UniversitätsSpital Zürich's middle ear models focus on the ossicles. By focusing on the movement of the ossicles, students can better grasp how the middle ear responds to varying frequencies and other abnormal functions. Since these are not commonly taught subjects, they can often be challenging to initially understand without the assistance of a physical model. These changes are important to model for students to increase understanding of the ossicle's movement.

III. UniversitätsSpital Zürich should include variability in future middle ear models.

UniversitätsSpital Zürich should create a model or models which depict the variety of anatomical differences that occur due to personal anatomy or in response to disease or infection. Current otology teaching models only depict the idealized versions of the middle ear anatomy without regard to anatomical variations or the effects of infections.

Additionally, identifying clear limits on the motion of the ossicles of our model based on various ailments and frequencies would increase the ability for students to learn from the model independent of an instructor.

IV. UniversitätsSpital Zürich should continually improve the model we have created.

UniversitätsSpital Zürich should focus on expanding the model this project has created by depicting the tympanic membrane in response to sound waves and adding more anatomical structures such as the cochlea. The inclusion of the additional anatomical structures surrounding the ossicles will provide students with an increased perspective on the ossicles overall interaction within the ear.

One specific addition we recommend for the model is a representation of the difference of vibration from an incoming sound wave at the tympanic membrane to the output at the cochlea. This would provide increased understanding to students of the primary role of the ossicles as well as how their proper functionality is key to the effectiveness of the ear.

UniversitätsSpital Zürich researchers should attempt to depict the movement of soundwaves through the cochlea. The model could show how vibration travels from the stapes to the cochlea. Additionally, a representation of the annular stapedial ligament, such as a rubber ring, to mimic the flexibility of this joint should be included. In order to show where our model fits in the ear, they should add a representation of the eardrum. Additionally, the soft connective tissues that comprise the middle ear and affix the ossicles should eventually be anatomically incorporated. However, the addition or creation of these connective tissues is recommended to first be modeled on their own without the ossicle's mobility and functioning cochlea. Further, the UniversitätsSpital Zürich should ask for student and professor feedback on how helpful their interactive models are to the lectures.

UniversitätsSpital Zürich should consult with biomedical companies to further understand the materials used to make the model feel and appear more realistic. This will aid their understanding of what materials besides 3D printed plastic, can be used to make better models. Potential alternative connective materials should be further explored in order to provide a more accurate representation of the subtle movements of the ossicular joints.

5.2 Conclusion

Our team was able to identify the learning gaps in hearing mechanics and propose supplemental teaching aids for students. Additionally, we discovered the most sought after part of the middle ear to model. We found value in variability and mobility within a teaching model.

The model we have created will allow students within UniversitätsSpital Zürich ENT department to understand how frequency affects the ossicles. UniversitätsSpital Zürich can then use our recommendations to further improve this model by adding anatomy and soft tissues. It is our hope that the model we have created and proposed recommendations given will help the UniversitätsSpital Zürich and the field of otology.

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Appendix A: Sponsor Description

UniversitätsSpital Zürich or University Hospital Zürich is located in central Zürich and is one of the largest teaching hospitals in Europe (SwissHealth, 2019). The hospital strives to, "...use our superior academic knowledge to treat a wide range of health issues, taking a personal touch and utilizing highly specialized and up-to-date research" (University Hospital Zürich, 2019a, para. 1). Starting in 2007, University Hospital Zürich became its own public institution necessitating its reliance to self-generated funds. University Hospital Zürich is one of five university hospitals in Zürich, Switzerland. Other affiliated university hospitals include the University's Children Hospital Zürich, Balgrist University Hospital, University Hospital of Psychiatry Zürich, and Center for Dental Medicine (University of Zürich, 2017). Table A.1 shows the different areas of employment at the University Hospital of Zürich and how many people each area employs.

Table A.1: Statistics of University Hospital of Zürich Staff by Position

(Source: University Hospital Zürich, 2019b, *Facts and figures.)*

University Hospital of Zürich Positions	Number of Staff
Physicians/Scientists	1,500
Nursing Professionals	2,600
Medical Technology, Therapy and Treatment	900
Non-Medical	2,000
Other	120
Apprenticeships	700

Additionally, the hospital has boards who oversee all decisions and departments (University Hospital Zürich, 2019c). The Hospital Advisory Board is responsible for management operations of the institution with responsibilities that include setting performance agreements, collaboration with other organizations, and corporate strategy. The Hospital Executive Board governs all of the decision making within the hospital with the responsibilities of fulfilling performance quotas and all tasks that do not fit under any other departments. The hospital boards and 8 other offices are all responsible for the University Hospital of Zürich operations and integrity (University Hospital Zürich, 2019c).

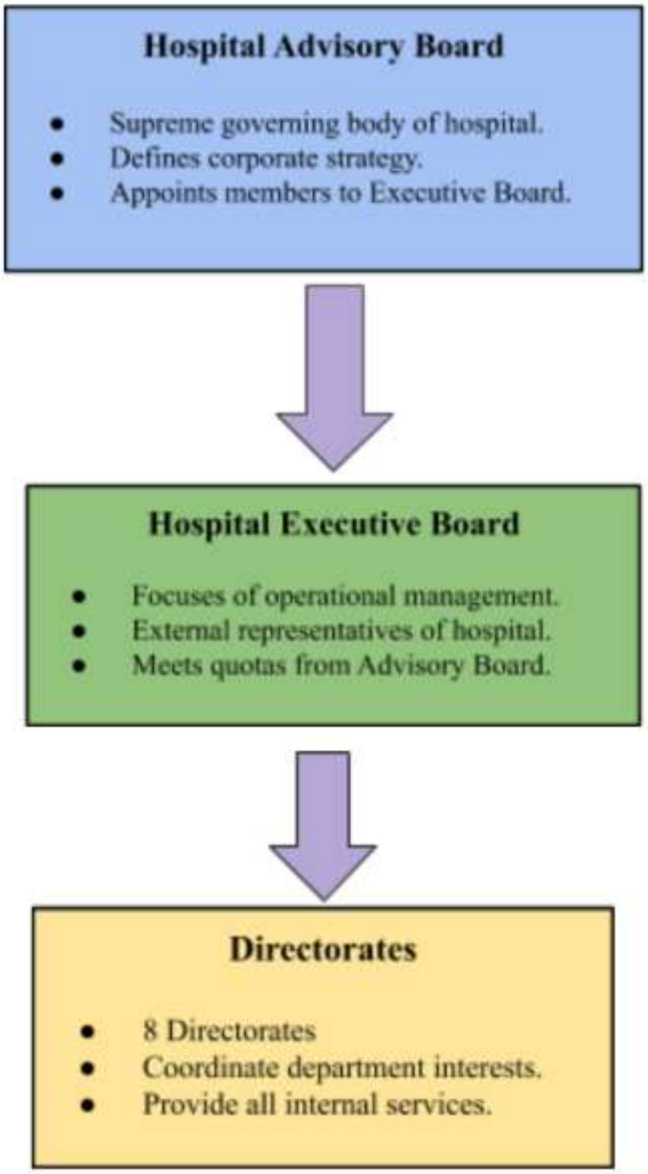


Figure A.1: University Hospital of Zürich Administrative Hierarchy
(Source: University Hospital Zürich, 2019c, *Hospital Advisory Board.)*

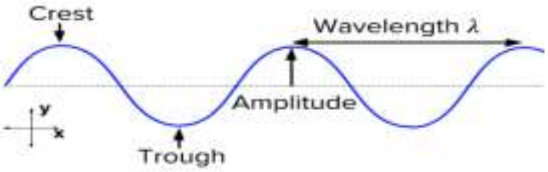
University Hospital of Zürich has many areas of specialization such as oncology, neurology, and otorhinolaryngology (SwissHealth, 2019). The department of otorhinolaryngology directly relates to this project because the primary focus is ears, nose and throat. The University Hospital of Zürich otorhinolaryngology department trains medical students and physicians' assistants. Due to this direct relationship to the education of new medical students and physician assistants, this part of the hospital will be of special interest to our project.

Our direct sponsor is Dr. Ivo Dobrev, a post doctorate at the UniversitätsSpital Zürich, who has been working at the University of Zürich since 2014. Dr. Dobrev's studies mainly focus on acoustics, bone conduction and middle ear mechanics (ResearchGate, 2019). One of Dr. Dobrev's most recent publications is the *Mechanical Properties of the Human Skull for Better Understanding of Bone-conducted Hearing.* As a postdoctoral researcher at the UniversitätsSpital Zürich, Dr. Dobrev's focus has been on the mechanics of hearing within the inner ear. Specifically, Dr. Dobrev focuses on identifying parameters influencing sound wave propagation and conduction within the human skull and comparing these findings with clinical results. Dr. Dobrev's unique field of research, experiences, and connections make him an extremely valuable resources for the success of this project.

Appendix B: Physics Reference Sheet

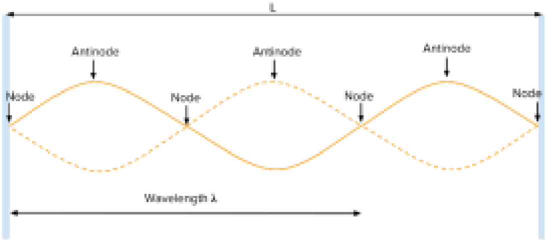
Wave: The transfer of energy and momentum through a series of points without transportation of actual matter. (Source: Wave characteristics overview, Khan Academy, 2018)

1.)



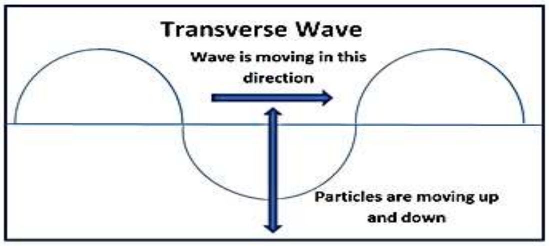
Standing Wave: Vibrational pattern that is created when two waves with the same amplitude and frequency moving in opposite directions collide due to interference. (Source: Standing wave review, Khan Academy, 2018)

2.)



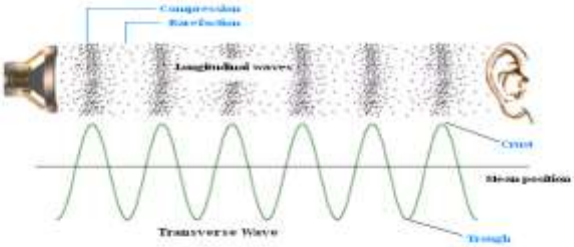
Transverse Wave: When particles of the medium vibrate perpendicular to the direction of the transmission of the waves. (Source: Rose, 2003)

3.)



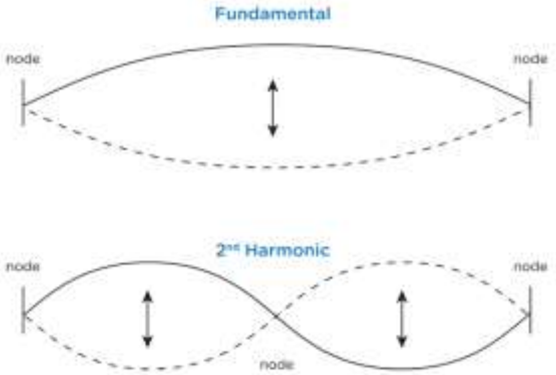
Longitudinal Wave: When the particles of the medium vibrate parallel to the direction of the transmission of the waves. (Source: How sound waves work, Media College, 2016)

4.)



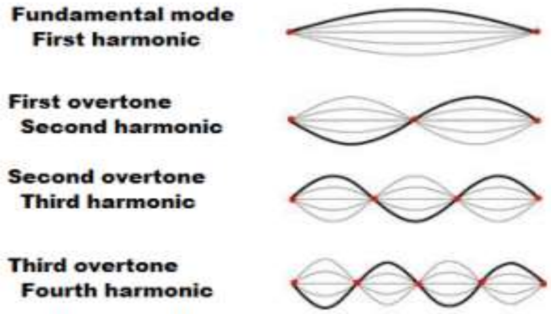
Harmonic Frequencies: Wave patterns that are created within specific frequencies of vibration. (Source: Holgate, 2017)

5.)



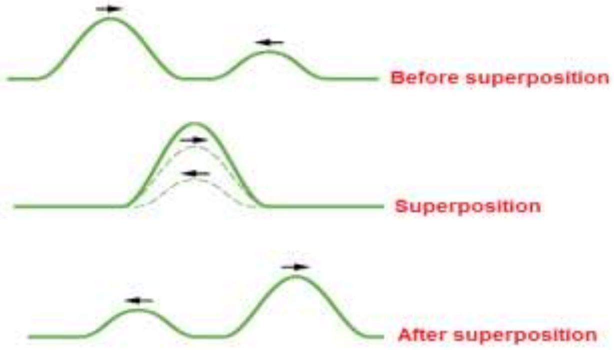
Overtone: Any resonant frequency that is above the fundamental frequency. (Source: Miller, 2011)

6.)



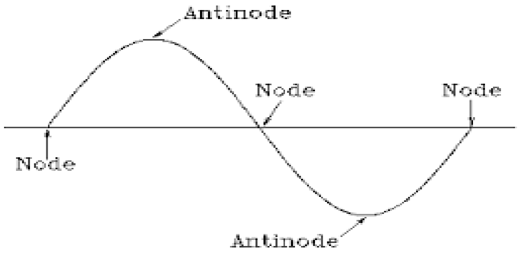
Superposition of waves: Two or more waves arrive at a specific point of the medium simultaneously, the resultant displacement at that point is equal to the vector sum of the displacements due to all waves. (Source: Lets Learn Nepal, 2019)

7.)



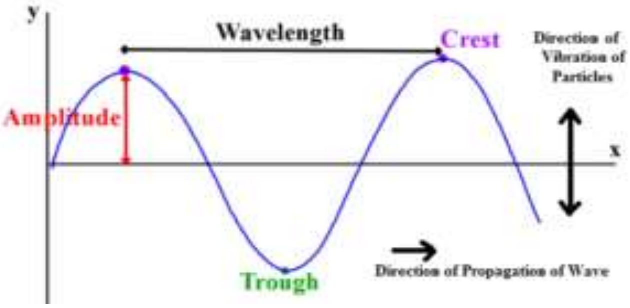
Nodes & Anti-nodes: Points that undergo maximum displacement within a vibration cycle. They remain in the same location and tend to vibrate back and forth between a large upward and downward displacement. (Source: National Schools' Observatory, 2019)

8.)



Mechanical Wave: This wave is a disturbance that is created when a vibration travels through a medium from one location to another. The energy is transported through the movement of the medium. The mechanical wave propagates itself through a medium by particle interaction. (Source: More, 2017)

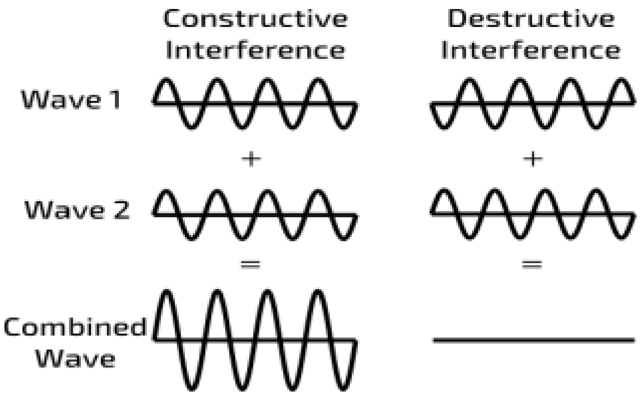
9.)



Constructive interference: When two waves superimpose and the resulting wave has a higher amplitude than the previous waves. (Source: Isaac Physics, 2014)

Destructive interference: When two waves superimpose and cancel each other out, leading to a lower amplitude. (Source: Isaac Physics, 2014)

10.)



Amplitude: Shows the volume and on a graph is the height of the wave from the starting point. Larger Amplitude = More Energy & Sound Intensity. Smaller Amplitude = Less intense sound volume. (Source: Verri, 2018)

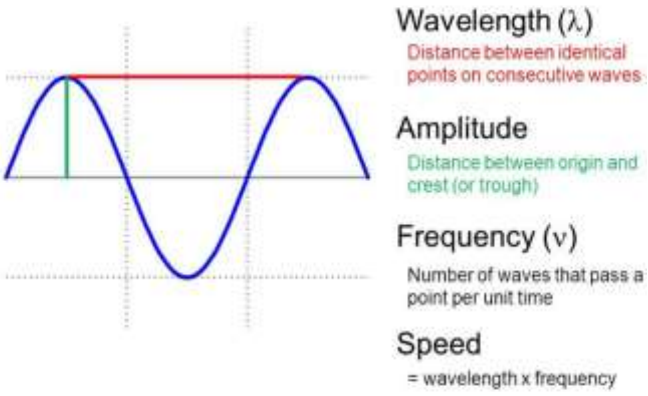
Frequency: The number of waves per second, and as the frequency increases, the pitch of the sound is higher.

Lower pitches = lower frequency

Higher pitches = higher frequency

(Source: Verri, 2018)

11.)



Suggested Interactive Websites:

University of Colorado Boulder sound wave simulation:

https://phet.colorado.edu/en/simulation/legacy/sound

University of Colorado Boulder wave interference simulation:

https://phet.colorado.edu/en/simulation/wave-interference

1.) Figure of wave. (Source: Wave characteristics overview, Kahn Academy, 2018)

2.) Figure of standing wave. (Source: Standing wave review, Khan Academy, 2018)

3.) Figure of transverse wave. (Source: Rose, 2003)

4.) Figure of longitudinal wave. (Source: How sound waves work, Media College, 2016)

5.) Figure of harmonic frequencies. (Source: Holgate, 2017)

6.) Figure of overtones. (Source: Miller, 2011)

7.) Figure of superposition of waves. (Source: Lets Learn Nepal, 2019)

8.) Figure of nodes and antinodes. (Source: National Schools' Observatory, 2019)

9.) Figure of mechanical waves. (Source: More, 2017)

10.) Figure of constructive and destructive interference. (Source: Isaac Physics, 2014)

11.) Figure of amplitude and frequency. (Source: Verri, 2018)

Appendix C: Interview Protocols for Professors, Graduate Students, and Physicians

The process for conducting interviews with the professors at UniversitätsSpital Zürich is as follows. The interview will involve one professor at a time with all team members present. Electronic and written notes will be used to record responses and if granted permission, voice recorders will be used to allow for playback of audio for analysis.

Due to the formal culture of Zürich, Switzerland, interviews will be conducted in the professional setting of hospitals and participant offices. Interviewees will be contacted in advance and will provide a synopsis of the project purpose and goals before an interview is scheduled. The consent script will be recited before proceeding with interview questions.

Consent Script

Our names are Nazanin Beigi, Colin Scholler, Dan Seeley, and Sarah Vazquez and we are students from Worcester Polytechnic Institute working on a 7-week research project on otology education involving basic physics applications. Our research team is sponsored by the UniversitätsSpital Zürich to develop better teaching models for graduate students. We would like to invite you to talk with us about your knowledge of the middle ear and your preferred teaching and learning methods. The interview should only take between 20 to 30 minutes.

The purpose behind this interview is to assess your preferred teaching methods in regards to otology and models used within the field of study. The information from this interview can be chosen to remain anonymous if desired. At the end of our project, this paper will be published through WPI’s library system.

The interview is completely voluntary. You can choose to not answer any question that you don’t want to answer and stop participation at any time. Before we begin, I will ask you some questions about permission:

- Do you agree to be a part of this interview?
- Would you like to remain anonymous?
- Would you be comfortable with us voice recording the interview? As mentioned in previous correspondence via email.
- Do you have any questions before we begin?

Interview Protocol - Professors and Researchers

- Which courses do you currently teach?
- Do you conduct any research at your University?
- If so, could you explain what research you are involved in?
- What types of teaching methods do you use when teaching graduate students?
- What types of electronic resources do you use such as PowerPoint or Google Slides?
- Do you ever request student feedback on your teaching methods? If so, how have students reacted to your teaching, if you are willing to share that with us?
- What do you know about the middle ear and the physics behind how we hear?
- Do you believe interactive models facilitate better learning? How so?
- Have you had any experience with interactive models? If so, please explain.
- What types of models would you like to see within the classroom learning environment?

Interview Protocol - Graduate Students at University Hospital Zürich

- What graduate program are you enrolled in currently?
- Do you have any research background? If so, what research have you been doing?

- What teaching styles do you learn best from in your program? Please explain why.
- What is your preferred learning style?
- Have any of your professors used any types of teaching models? If so, please explain what they were and how they were used.
- Are you familiar with undergraduate level physics concepts regarding hearing such as sound waves and vibrations? If so, please explain what you know.
- What do you know about the middle ear and how it functions?
- Do you believe interactive models facilitate better learning? Why or why not?
- Have you had any experience with interactive models? If yes, please explain.
- What types of models related to the human hearing system would you like to see within the classroom learning environment?

Interview Protocol - Physicians at University Hospital Zürich

- What type of specialist are you in medicine?
- Do you conduct any research in addition to being a physician?
- If so, could you explain what you are working on?
- During your time in medical school did you ever use teaching models? If so, please explain.
- If so, for what field of study and which parts of the body?
- Did you enjoy being taught by professors who used models?
- Do you believe interactive models facilitate better learning? Why or why not?
- Have you had any experience with interactive models? If so, please explain.
- Would medical schools benefit from more interactive models? Why or why not?

- How much do you know about the middle ear and how it functions as part of the human hearing system?
- What type of components would you like to see in an interactive model for hearing? Please explain.

Interview Protocol – Biomedical Companies

- What are your models used for?
- What materials are the models made of?
- What is your process to make these models?
- What methods have you found most useful to achieve realism?
- How anatomically accurate are the models?
- Are the models mechanically similar to real temporal bone and middle ear?
- Where do you get your CT data?
    - What software do you use in making the model?
- Does the model include components of middle and inner ear, like the ossicles or cochlea?
- Do you request feedback from those who purchase your models?
- What kinds of functionality do your models have?
- Are normal functions as well as dysfunctions shown?
- Which part of the model do you wish could be accurately represented?
- Have you faced any challenges making your models?
- What is the primary audience for the models?
- What is the recommended time medical students should spend on the simulation models to become proficient?
- How did you improve your ossicle model and how long did it take

Interview Protocol – Model Feedback

- Do you find our model to be clear and easy to understand?
- Do you think it represents the functionality of the ossicles well?
- Are there any other ways we could show the functionality?
- Are there other functionalities that you find may be important to try and represent with this model?
- Future suggestions/recommendations on our model?
- Do you find this model useful for a classroom environment?
- What are some advantages and disadvantages you think this model has?
- Do you think the color differences was helpful?
- Was the scaling of the model appropriate?
- Based on this model, what are some areas that you think need improvement?

Appendix D: Interview Manuscript; (Anonymous)

This Interviewee has asked to remain anonymous.

Colin Scholler: “What kind of teaching methods do you use when you’re teaching graduate students or otology students?”

Interviewee: “Are you familiar with Moodle? This is where the students find manuscripts, exercises, online tools and print it. The teaching is a mixture of just frontal teaching and teaching of theory and exercises as well as exercises like indirective exercises. Students prepare some questions and they are asked voluntarily to teach the other students on those questions. If they prepare well they get bonus points for that exam. 70% is frontal teaching and theory and the other parts are exercises and quizzes and whether they take part interactively. The material, they have access to it through the Moodle course.”

Colin Scholler: “So the students also provide information on their findings?”

Interviewee: “Yes, one is asked for example to prepare an overview on an element and then I give him pages that are selected out of a book or tutorial and he reads through it and prepares it in slides and he presents it to the class. This is sometimes called flipped classroom. This is only one method for students. Another one is I tell them the next lecture we will talk about exercises x, y, and z. They can prepare the exercises for the next lecture and they can show the other students how they did it. If nobody wants to tell other students how they did it, I will step in. If they do it, they will get bonus points for the exam. Everybody is given the option of taking part in the exercises. Bonus points means compensate for a mistake on the exam. This is my concept of motivating them to take part in lectures and continuous learning in lectures.”

Colin Scholler: “Do you request feedback from your students on your teaching methods?”

Interviewee: “Yes because it is now my fourth year of teaching, it is obligatory to get assessed each semester at his first office in the first three years of his teaching. If I introduce new methods, I ask for specific feedback. A questionnaire that I fill out and post and the students fill out anonymously online and give me feedback. I don’t know who filled out the information but I ask specific questions on the new methods and see whether they find it useful. Each second year a questionnaire is sent on my teaching styles, behavior in a classroom setting and sent out. It’s a standard questionnaire.”

Colin Scholler: “How do students react to your teaching methods based on the feedback you received?”

Interviewee: “They have teaching materials, they have my way of teaching and personality. Personality they have responded to me to be helpful teacher. Way of teaching: they tell me they can take part whenever they want within a lecture. Teaching materials- get a minus because they do not like the manuscript and would rather have it digitally, as it is a lot easier. Something I am working on right now.”

Colin Scholler: “What is the manuscript that you had mentioned?”

Interviewee: “Relax course - This is what I use to send the students information to inform the students about lectures, where we will be, and what the topic will be. The information here are things that are not directly related to the lecture, but are good information to know for the lecture. I tell them to go through something because this is what you should know and get an overview and have a common understanding so they are prepared for the lecture topics. There are also exercises. I can tell them we are going through exercises and this is where they can practice their knowledge. Then the concept of flipped classroom is found here. I have up to 19 lessons and they go here and decide what lesson they want to use to teach the students in the classroom. Once they choose the topic, they can find the tutorials, theories and all the necessary materials for the lesson. They can work it out on their own and at the end they come to me prepared for that specific lesson and we integrate it within the lecture and they decide when to do this. They take quizzes here as well. If I went through introduction and modeling, I tell them now you can do the quiz. They go on the course and take a quiz that covers the related material."

Colin Scholler: "Do you use physical models at all?"

Interviewee: "Not within my lectures. Don't regularly use them but I did for last semester. In the lab we are doing experiments about active implant and were modeling it with our own models and simulations. To do it though, I have to skip other things. The students did give me feedback and told me they found it very valuable. I believe that physical models do facilitate better learning. Sometimes you need to compare simulation with experiments and that model specially did that. I believe models should be part of the lecture."

Colin Scholler: "Can you briefly tell us a little about your research regarding the middle ear?"

Interviewee: "Adhere bone company — did measurements on the system on the different motions and excitations of the system and modeled it and compared it in order to improve the coupling to the bone. It's a system where they have to screw or fix it permanently to the bone but it's a temporary fixation with a sticker and adhesive adapter. They wanted to know what could be done to improve this coupling. We are modeling the ear in order to improve diagnosis and the understanding of the way of hearing. Normally you take measurements on an individual patient and compare it to the normal range of people. There are large differences so the normal range is also large, such as the standard deviation. If you compare an individual patient to the normal range you cannot get specific because the range is so big. We are also using modeling to improve implants”

Appendix E: Interview Manuscript; Dr. Christoff Röösli

Daniel Seeley: “In medicine what do you specialize in?”

Dr. Röösli: “In otology”

Daniel Seeley: “What kind of research are you working on?”

Dr. Röösli: “My main project was on bone conduction hearing and besides that I am involved in cochlear implant research and middle ear mechanics as well as histology of the middle ear”

Daniel Seeley: “Did you ever use teaching models or see them in school?”

Dr. Röösli: “Not so much, there were some plastic models around but not so freely available”

Daniel Seeley: “Do you use models to teach?”

Dr. Röösli: “Yes, I use models for the residents if they have to learn the surgical anatomy they have to work on the falcon bones to practice on them and get familiar with the 3d anatomy and the other option is to use computer simulation”

Daniel Seeley: “What are your thoughts on physical vs simulated models?”

Dr. Röösli: “Not sure, the physical models are useful because you can turn it around and look at it. The simulation look good on computer but sometimes it's hard to estimate the distances between the different structures and I think you should have both”

Daniel Seeley: “Do you teach courses?”

Dr. Röösli: “I teach medical students, theoretical and practical. Teach nurses that are trained to work in the OR. Also teach the engineering background and anatomy for the cochlea.”

Daniel Seeley: “What components do you want in a model?”

Dr. Röösli: “We need all the structures for the middle ear ossicles. The nerves, the blood vessels, the dura. It would be great to have movable ossicles. That is something we don't have yet. Moveable by hand and so you could touch it and see it move would be better.”

Daniel Seeley: “How do you teach otology classes?”

Dr. Röösli: “Very often just use slides and images because if there is a large audience it is difficult to pass around a model that reaches the students and back around. I use videos from the OR to teach the class. First I use sketches and then a real case.”

Daniel Seeley: “Do you request feedback request about teaching and class?”

Dr. Röösli: “Yes they have to get feedback but I don't get it back.”

Daniel Seeley: “What about the middle ear is important?”

Dr. Röösli: “See the ossicles move because with the sound waves it would be too small of a change to actually see it move. I think there are existing models that help show simulations of the ear but they lack details. It can be digital or physical but if they have details it will be better. “

Daniel Seeley: “How do you engage students?”

Dr. Röösli: “Use real patient cases to teach anatomy and physiology and sometimes I have one patient that comes to the lecture and show the findings and ask the patient questions and have the students observe.”

Daniel Seeley: “What challenges do you face when trying to teach?”

Dr. Röösli: “Complexity of it and because they did not have a strong background in physics so it is difficult to get started”

Daniel Seeley: “Can you give us a brief physics overview of the ear?”

Dr. Röösli: “No, not enough time to get into physics so they need to go back into the book and read because I cannot go over all the details.”

Appendix F: Interview Manuscript; Merlin Schär

Nazanin Beigi: “What graduate programs were you enrolled in?”

Merlin Schär: “International PhD program of the CNC. Neuroscience doctoral program but in my research I am working with topics of biomechanics of the middle ear I am investigating the interaction between soft tissue properties in the middle ear and the geometry of these structures. Since our group is part of the CNC we are all affiliated with this program.”

Nazanin Beigi: “What was your undergraduate program?”

Merlin Schär: “Medicine, I am basically a medical doctor that opted for research”

Nazanin Beigi: “What medical classes did you take?”

Merlin Schär: “In Switzerland, the school is different than in the U.S. In Switzerland, you finish high school, apply for medical school which is a package of 6 years and have to decide very early. The first two years of medicine cover the basic science that undergraduate covers for you guys in the U.S. the last 4 years are more clinical”

Nazanin Beigi: “Did you take physics courses?”

Merlin Schär: “Only had one semester of physics, which is very little. Due to my project, I had to take more physics courses.”

Nazanin Beigi: “Did you use models in medical classes?”

Merlin Schär: “Yes, in the second year of medical school you will have a dissection lab where a group of students will work on a donated body and over the course of the year you would dissect and prepare different parts of the body to get familiar with its anatomy and they also had a large anatomical collection of fixated body pieces which are used to get an idea of spatial relations between anatomical structures. There was also CT scans of the bodies that were donated and dissected."

Nazanin Beigi: Do you find CT scans easier to work with or the human body?"

Merlin Schär: "The actual body is preferred so you can get an idea of how things are related to each other. We had a lot of textbooks but no such as vr or 3d. I prefer hands on models. There was a section of class that taught skull base anatomy - some parts of this anatomy were hard to memorize. For this they had a physical model that you could take apart and reassemble and it was one of the most beneficial things to have."

Nazanin Beigi: "What types of abnormalities do you see in models?"

Merlin Schär: "Requirements from body donors- would get rejected if it didn't fit the requirement. Still, there are a lot of anatomical variations and found abnormalities."

Nazanin Beigi: "What part of the ear do you believe to be important to model?"

Merlin Schär: "The middle ear is most important. Looking at defects is really interesting for me. Looking at the complex tissue structure and t's alterations like ossification, or inflammation. For a clinician, not so sure what they focus on. For most, the middle ear is just a mechanical transformer to transform vibrations into the fluid of the cochlea. For them, tympanic membrane should be included a long the ossicles as well as the ligaments that make up the ossicles."

Nazanin Beigi: "Do the ligaments and muscles attaching to the ear have any effect on hearing? And would this be important to model?"

Merlin Schär: "Yes, they contract if sound reaches a certain threshold but it is not very well researched. If you could somehow mimic air pressure in the middle ear, that would be helpful or the epithelium that covers the ossicles."

Nazanin Beigi: “What is your learning style?”

Merlin Schär: “I am a visual learner. What helped me learn better is that some of the professors were very enthusiastic about the course. There was a lot of dedication to the courses.”

Nazanin Beigi: “Did you use handouts in your education and did you find them to be effective?”

Merlin Schär: “Yes through the platform they upload all the material to have it in class. Must understand the basics of physics - do not need to be a mechanical engineer but must understand some of it.”

Nazanin Beigi: “What were some differences between medical and engineering classes?”

Merlin Schär: “Engineering classes were much more vigorous. Medical school we didn't have exercise sheets to solve. Engineering courses were more problem solving.”

Appendix G: Interview Manuscript; Prof. Dr. Alex Huber

Colin Scholler: “During your time in medical school have you ever used teaching models or were you taught with them?”

Alex Huber: “Not in otology but in other things such as anatomy. This is a typical field for models, also basics of physiology and physics. Also models were used to show heart diseases but in different ways like physical models or electronic models.”

Colin Scholler: “What was more beneficial, physical or computer models?”

Alex Huber: “It depends, with some models its possible to show things like in computer models you got to model pressure and frequency easily while in the anatomical models you can see all the structures and put together how the valves work. Both models have their advantages and their disadvantages.”

Colin Scholler: “Did you find the models useful?”

Alex Huber: “Yes, it is of high importance to have a sort of model to help show something, whatever it may be because it is really difficult to describe complex things. Pictures in their own way are even models.”

Colin Scholler: “Do you teach any courses and if so, what are your teaching methods?”

Alex Huber: “I teach ENT lectures, covering otology and introductory courses. In the courses we typically have patients instead of models. The student will have a conversation with the patient, examine the patient, and then we have a general review of the findings of the interview and different diagnoses. Then in the lecture, one person will discuss the material while everyone else gathers the information.”

Colin Scholler: “Do you use physical models in any of your current courses?”

Alex Huber: “Not at the moment, but I have experience using them. There is one big model that is outside of the classroom but I do not find it very helpful. We also have some anatomical preparations.”

Colin Scholler: “What types of models would you like to see?”

Alex Huber: “Optimal model would be something that incorporates everything. This would be where you could model a physiological state as well as a pathological state of the ear. You could see how the ear is in a regular situation and what happens if there is a chronic infection or a disease like Otosclerosis or a tumor. Where we could show how this would influence hearing and maybe tinnitus. Or show how the semicircular canals are being affected, that would be the best case scenario.”

Colin Scholler: “What is the most important part of the ear to you?”

Alex Huber: “One thing that is difficult is the three ossicles following their joints. Particularly the stapes in the oval window. The other part is the basal membrane in the cochlea.”

Colin Scholler: “Besides the joints what are the other issues with the middle ear?”

Alex Huber: “The ligaments, particularly the stapedial ligament is very important and how it is a fixed muscle. This is the most important one. Then in pathological situations, it's how the ossicles are affected in terms of reduction in structure, thickness of incus, change of thickness, chronic infection changes. This is something that would be of importance in a pathological situation. The structure and behavior would change as well in diseases such as Otosclerosis.”

Colin Scholler: “Any diseases involving the ossicles?”

Alex Huber: “Otosclerosis, chronic ear infection, eardrum perforations, tumors and trauma.”

Colin Scholler: “Can you tell us about the function of ossicles and how frequency affects their movement.”

Alex Huber: “The basic function of the ossicles is to transmit sound and transform it from air conducted waves to material conducted waves in the fluid filled cochlea and at the same time to uncouple those very tiny motions to the relatively large motions. To still have a good transmission of the smaller vibrations.”

Colin Scholler: “Movement of the ossicles can change?”

Alex Huber: The motion is a rotation around the malleus and incus ligament. There is a rotation around this axis and an even out motion of the stapes. The tympanic membrane has a one model motion. This goes up to the resonance frequency to around 1200 maybe 1400 hertz depending on the subject. Then it breaks up and becomes complex, has a complex motion of the eardrum. Has travelling waves that move differently. The ossicles start to rotate in a complex fashion, not anyone around the axis. They have independent rocking motions with the different frequencies.

Appendix H: Interview Manuscript; Dr. Jae Hoon Sim

Nazanin Beigi: “What are the course topics you teach?”

Jae Hoon Sim: “Mechanics of hearing, but we focus on the middle ear part.”

Nazanin Beigi: “What about the middle ear are covered in these courses?”

Jae Hoon Sim: “We isolate how the middle ear sound occurs and how to regenerate the middle ear functions in patients such as sound transmission or a type of damage made in the ear.”

Nazanin Beigi: “Is your focus on sound or bone conduction?”

Jae Hoon Sim: “Now I am in charge of middle ear research and teaching.”

Nazanin Beigi: “Do you ever use physical models?”

Jae Hoon Sim: “Yes but it’s not showing function it is only for visualization.”

Nazanin Beigi: “What is your focus in regards to the middle ear?”

Jae Hoon Sim: “Which condition of the middle ear will lead to better outcomes for specific patients, this is the focus and most important.”

Nazanin Beigi: “Please elaborate on what you mean by conditions?”

Jae Hoon Sim: “Surgery on ear to improve their hearing.”

Nazanin Beigi: “Do you think interactive models are good for learning?”

Jae Hoon Sim: “Yes, if we show 3D on screens such as computer models would be helpful.”

Nazanin Beigi: “What do you want an interactive model to show?”

Jae Hoon Sim: “The ossicles moving in response to sound waves.”

Nazanin Beigi: “Do you review physics within your courses?”

Jae Hoon Sim: “Yes, most of the students have medical background but no background in mechanics. Simple series in mechanics which are necessary to understand the class is the area I explain.”

Nazanin Beigi: “How much time do you spend on the physics in the lecture?”

Jae Hoon Sim: “About an hour with handouts.”

Nazanin Beigi: “What teaching methods do you use?”

Jae Hoon Sim: “PowerPoints, Key concepts page about things they should remember.”

Nazanin Beigi: “Do you ask for feedback from your students in regards to your courses?”

Jae Hoon Sim: “Yes but I cannot see it, it is mandated by the university.”

Nazanin Beigi: “Did you take any biology courses?”

Jae Hoon Sim: “No, but during my PhD my research topic was about hearing mechanics.”

Nazanin Beigi: “What are the differences between engineering courses and biology courses?”

Jae Hoon Sim: “The engineering courses are based on more problem solving, more math based. Biology courses are more remembering.”

Nazanin Beigi: “Do medical students struggle with physics concepts?”

Jae Hoon Sim: “Yes so we always have to explain the basics.”

Nazanin Beigi: “What is important to know about physics to understand the middle ear?”

Jae Hoon Sim: “Orthopedics is necessary to understand and physics is an important aspect.”

Nazanin Beigi: “How do you teach your courses in such a short time frame?”

Jae Hoon Sim: “Show demonstrations in the lab and the class is usually a good amount of the day.”

Nazanin Beigi: “Do you think hands on models are more beneficial in a classroom setting or digital?”

Jae Hoon Sim: “Hands on is better but all the problems that go with making that, then I would choose the digital instead.”

Nazanin Beigi: “What is your current research on?”

Jae Hoon Sim: “Using basic science of hearing we are researching about protection of the middle ear and performing clinical studies. They are developing new processes and test the process and look at the parts that infect the ear.”

Appendix I: Interview Manuscript; Phacon Interview - Robert Haase

Colin Scholler: “What are your models used for primarily?”

Robert Haase: “Used for generally for hands on training so that surgeons and residents can teach on our models for example specific surgeries like inside the cochlear implant, to draw mastoidectomy or let’s say also for professors to get the ends of the scope inside the nose, our models are used globally for hands on for teaching for education purposes.”

Colin Scholler: “What do you make your models out of?”

Robert Haase: “We use different materials, different technologies in order to assemble our models so you cannot reduce to just one type of technique. We combine different techniques and different material, because you have also soft tissue material, bone material also the bone consistency is different it's not the same so you have a lot of outer shell you have softer inner shell and this of course also you have to adapt to that model so that you have a realistic feeling.”

Colin Scholler: “Is that the case with the temporal bone trainer?”

Robert Haase: “Yes, I cannot give you the exact materials but we use different types of materials in order to achieve the realism of the temporal bone because let's say the ossicles are different than the mastoids and therefore you have to combine different materials.”

Colin Scholler: “When you are making this material do you use 3d printing or molding?”

Robert Haase: “Different techniques, yes we use prototyping techniques but that is one part of the process. We also use molding, we use different prototyping. We actually acquire from each technique is the best solution for us of course in relation to cost effectiveness and in relation to realism because you have to balance every time of course realism and the model itself and cost effectiveness. In the end nobody would purchase the model if its too expensive and that is why we care."

Colin Scholler: "What methods have you found most useful in order to achieve that realism?"

Robert Haase: "We often do otostudies, studies with surgeons so it is iterative over years also and then we have founded the company in 2007 so we had developed our first type of bone during that time. Of course, during that time we changed many many steps, the bone, and the soft tissue material and so on because we did studies and received feedback from the surgeons and the hands on courses. Also we receive feedback from the companies that use our models as well when they use our model to present an implant. We continuously improve and make our models better. In the company we are mostly engineers, computer scientists and so on. Of course, you have to prove your model in different iterations let's say with the surgeons and also the functionality must be optical so that everything comes together in a realistic model."

Colin Scholler: "What kind of functionality do your models have?"

Robert Haase: "Depends on your case. For example if you have the temporal bone or flexible ossicles. The ossicles need to be flexible, it is important that you identify the ossicles and that they are moveable. There are different techniques and surgical interventions in regards to the ossicles so they are plastic and you cut the ossicles which is why the model needs to be functional. Another example is our nose. Inside the nose you have terminates and they need to be flexible which is what makes auto functionality an important aspect."

Colin Scholler: "Do ossicles have mechanical similarities in regards to movement with sound?"

Robert Haase: "No not really."

Colin Scholler: "Is there anything else you wish your models had or are trying to develop?"

Robert Haase: “This is our special strategy and aim on the one hand we would like to have variety in different models. Imagine when you are a surgeon, you would like to train on not only one case, of course you have varieties like special pathologies. It is different when you operate on a child or an adult. The pathologies are different, or even a very specific case you would like to train on. One side is increasing our variety on models so that surgeons have options to choose from for the training. Also, we would like to expand our knowledge and philosophy on how to do different disciplines. We have started with the temporal bone, sinus, lumbar spine but we would like to expand it even further to the rest of the body.”

Colin Scholler: “What types of cases do you have now other than the standard ones?”

Robert Haase: “We have for example special pathologies like in the temporal bone, such as the common cavity pathology. This means your cochlea is merged together. This is a difficult case for patients because the surgeons try to enter the electrodes. Other things like cholesteatoma. Some other things we have in the nose with the low line skull base so that means inside the nose you have a low line skull base and you have to make sure when you are operating on the nose you do not go inside the brain.”

Colin Scholler: “What's the primary audience on the models?”

Robert Haase: “They are residence and those on hands on education courses, medical companies, professors, training and skills labs, company trainers and more.”

Colin Scholler: “How much time do you recommend medical students use the models?”

Robert Haase: “That depends on the country, on the region, on the model type. To give you an example such as the temporal bone, if you were to learn to do surgery on it, it will take at least one hour just to drill through the model.”

Colin Scholler: “Do you request feedback from those who make purchases on your models?”

Robert Haase: “Yes, it is our job to acquire such information to identify the problems and improve the models.”

Colin Scholler: “Any challenges you have faced as tasks for you?”

Robert Haase: “One challenge for us was to make the ossicles moveable. Imagine you have tiny ossicles with thin muscles and before we had a model that was flexible but it was different as it was rigid. It was hard to perform surgery on and to cut the membrane. The more rigid, the harder it is to cut. This is dangerous and leads to an inefficient model. It was challenging for us.”

Colin Scholler: “What software do you use to make the models?”

Robert Haase: “We use multiple different software to take virtual models to cut the temporal bone for example.”

Colin Scholler: “How did you improve your ossicle model and how long did it take?”

Robert Haase: “On that specific model, it took us more than half a year. When we founded the company it actually took years to develop anything such as a temporal bone. Then we kept going in and making changes, over and over again. It happened through trials.”

Appendix J: Interview Manuscript; Prof. Dr. Vartan Kurtcuoglu

Sarah Vasquez: “Do you conduct any research at this University?”

Vartan Kurtcuoglu: “I do.”

Sarah Vasquez: “If so, could you explain just a little bit about what you're involved in and what you’re working on?”

Vartan Kurtcuoglu: “So, my expertise and research I do is in fluid dynamics and the human body, both using computational tools but also experimental ones. I look at transport processes that are associated with fluid flow, so this is in the brain for example cerebrospinal fluid dynamics, cardiovascular system exchange of substances, also kidney. So, anything human body and fluid flow that where we basically could be doing research.”

Sarah Vasquez: “Which courses do you currently teach, if any?”

Vartan Kurtcuoglu: “I teach cardiovascular physiology to medical students. Then, I have kidney respiration to teachers, so teacher training, and teacher training program. I have a course that is on cross-disciplinary research and development between engineers and medical doctors. That’s both ETH and the university. So then we have students from both sides. I teach practical courses in physiology, that’s various things like including in the hearing practical course and so next semester I will be teaching the ear, also physiology, to medical students. I have not started that one yet.”

Sarah Vasquez: “What type of teaching methods do you typically do within your courses and do they vary between, of course, your audience of teachers, medical students, engineers?”

Vartan Kurtcuoglu: “Yeah, it depends a little bit on the size of the class. So, for the medical students where you have maybe 400 people then it’s just a frontal lecture using

PowerPoint slides and maybe showing movies and sound files, for example, for auscultation and stuff like that. For the practical courses we have physical models that we use, we use demonstrations, for example, how different frequencies can be heard at different perceived loudness even though the sound pressure level is the same, how our ears can distinguish from our brains the location of the sound source. These are really practical examples. Doing audiometry with the students of research setup, so that's really hands-on. And for the course with the medical students and engineering students it's mostly project based. So they get assigned a project, they can within that project define more or less what they want to do. And we coach them and help them in the process but it's a project based course."

Sarah Vasquez: "Do you guys use any sort of online platform where you post anything, PowerPoints, lectures? Or are they submitting assignments online?"

Vartan Kurtcuoglu: "The University has a system where we can share slides, get assignments back. It's kind of like a collaboration platform that is really made for that purpose. We use that for the larger classes. The smaller ones, we have a server, it's kind of like Dropbox, students can just place files and we can have a less formal exchange."

Sarah Vasquez: "Do you ever request student feedback on how they enjoyed your teaching or the course in general?"

Vartan Kurtcuoglu: "Yes"

Sarah Vasquez: "How have they typically reacted to your teaching style?"

Vartan Kurtcuoglu: "It depends on how you solicit the feedback. So, some students, if you just ask, give us some feedback, then you just get a score. Some will find it too difficult, some will find it too easy, and so it's difficult to get the answers out. And those who usually come volunteer information are the better students. And then again it’s biased feedback so I find it difficult to get unbiased feedback from students.”

Sarah Vasquez: “Do you believe interactive models facilitate better learning. Especially within your physiology classes?”

Vartan Kurtcuoglu: “I have to say yes because we produce interactive models, computational models. We have a larger project that is sponsored by the University of Zürich to teach cardio renal system, so the interaction thereof, where you don’t just read from a physiology textbook, but you can adjust parameters. You can have patient cases and try to reproduce them. So how much the students at the end profit from it depends very much how much time they invest in it. If you have a system like that you really have to spend hours on it if you want to understand, otherwise your better off with a text book, and it’s faster.”

Sarah Vasquez: “What types of models, besides computational models, do you think would be beneficial for a learning environment?”

Vartan Kurtcuoglu: “You mean, for example, physical models or?”

Sarah Vasquez: “More physical models, do you think those would be beneficial as well, or do the computational models have a little bit more of an advantage?”

Vartan Kurtcuoglu: “Just purely fact based computational models are superior because you can include much more at a lower cost of much less maintenance, but they're less well received by the students than the physical models for sure. Not just by the student but also if we an interaction with our clinical partners for example it's difficult for them to understand what the physical model does. Just to give a very simple example, if you wanted to teach someone that a restriction in the cross section of a vessel reduces the pressure drop then, you can have it on the computer very easily done. You could have quickly change some parameters if you have the same thing physically, exactly the same thing, then people will like the physical model better because even though you might have the same graphical representation it is received much better when you can touch it."

Sarah Vasquez: "So you generally have much better feedback when it's physical?"

Vartan Kurtcuoglu: "Yeah, for sure."

Sarah Vasquez: "You also teach a couple medical courses. Would medical schools benefit from more interactive, physical models, if they had functionality for instance and could move in response to let's say sound waves to the middle ear?"

Vartan Kurtcuoglu: "It depends a little bit. Principally, yes. But, it depends on the time that they have. In our curriculum medical students don't have much time, at least not in the bachelor plus beginning master's, before they go into the clinics. The question would be where to place them. The place are the practical courses when we already have different setups. This would be in addition to it but the students would spend maybe 10 minutes with that, not more. Because there is not time to do much more."

Sarah Vasquez: "What type of components would you like to see in an interactive model for hearing?"

Vartan Kurtcuoglu: "The one thing that the students have a hard time grasping is impedance matching especially if you're not from an engineering curriculum then the concept of impedance is not quite clear. For hearing, that's very important. That's something where you could adjust impedance, and not just having the physiologic situation but also changes in impedance. I think that would be quite helpful. Other things, for example, if you have a perforation of the eardrum, what does that mean? If you have any ossifications, stiffening of the middle ear structure what would that mean? To replicate clinical or have a physiological situation I think would be helpful."

Sarah Vasquez: "You had mentioned that you teach about the varying frequencies. Do you have a model for that or do you talk about it in general?"

Vartan Kurtcuoglu: "What we have is basically a signal generator, amplifier, and speakers then you can set up sound pressure level and let the students listen to it if they hear anything."

Sarah Vasquez: "So it's interactive where they listen to it?"

Vartan Kurtcuoglu: "Yes, exactly."

Feedback on Physical Model

Colin Scholler introduces and describes model.

Colin Scholler: "Do you find this model to be clear and easy to understand?"

Vartan Kurtcuoglu: "I think it depends on how you represent or how you actually point to the different muscles and tendons. For someone who just would like to have a general idea this is fine. You just need to imagine how the middle ear is set up. Medical students have learned their anatomy quite well so they would want to have referencing the muscles and tendons to what they actually see. That would be important to have the connection points well established and anatomically correct."

Colin Scholler: "One potential application of this model that we've been looking at is to show the movement of the ossicles at various frequencies and how that changes. Do you believe this would be advantageous in that application?"

Vartan Kurtcuoglu: "Can you reproduce different modes, because you can have quite complex modes?"

Colin Scholler: “Yes, it mainly relies on the teaching instructor to move them to show that. The elastics are meant to represent to default axis of rotation and still allow those more advanced on to be done. Once you have it isolated from the support structure, you can grab it and move it around.”

Vartan Kurtcuoglu: “We have physical models that are not quite well connected but you have basically the head and you have any structure in this case the ossicles that you can remove and put back in place like a 3D puzzle. What they do not have, and which is difficult to see, is how they interact in 3D space. For me that would be a more important new feature. Being able to mainly excite it as you would have with the eardrum and see what happens and what comes out at the other end. Also, in terms of the lever that you have, impedance matching aspect, if that could be visualized, I think that would be nice.”

Colin Scholler: “Are there any other ways we could show the functionality?”

Vartan Kurtcuoglu: “It would probably be difficult if you wanted to look at actually vibrations. If you now enlarge your system, you could go into lower frequencies. You basically have a matching system in terms of size. That could be interesting, especially if you could then go to low frequencies that are visible as actual vibrations and see how these would be transferred. Because it's very difficult to imagine for example at 1500 Hz how these little bones actually move, it's not quite intuitive.”

Colin Scholler: “Do you have any direct future suggestions with this model?”

Vartan Kurtcuoglu: “If you could think of an actuation system and a way of reading out what is happening. It's not the same thing. Imagine if you have a pen and you're vibrating it, you have a trace on the paper. If you have the input on the one side and then the transmission to the inner ear, how could you do a way that the students could see that there is something moving and what is happening. I think that would be nice."

Colin Scholler: "With this model in mind, what are some advantages and disadvantages that you see with this over what is currently around?"

Vartan Kurtcuoglu: "I think the connections that you do have now, the rubber bands, that's an advancement over what we have. If you have this suspended in the frame, it's also something. You could really leverage that one, you can move it in place, pick it up and actually see how they interact. That would actually be able to give you more advantage over what is available right now."

Colin Scholler: "What do you think the other models that are currently available do better than this one?"

Vartan Kurtcuoglu: "If it's just anatomic models and they have the right size. Then you actually see, for example, what the stapes looks like and the reaction looks like. In this case, if you don't have reference, then it's difficult to say well this is 20 times larger."

Colin Scholler: "Do you think the color differences was helpful?"

Vartan Kurtcuoglu: "I don't know if the colors really add. But I may also be biased so that's probably something you should ask students what they think."

Colin Scholler: "Where do you think that bias comes from?"

Vartan Kurtcuoglu: "Because I know the structures."

Colin Scholler: "Do you think the scaling that we used was appropriate?"

Vartan Kurtcuoglu: "Even though you said what you're scaling was before on the screen I was expecting them to be smaller."

Colin Scholler: "Do you think that was a good choice, the size that we chose?"

Vartan Kurtcuoglu: “I wouldn't make it any bigger. No, I think its fine. If anything, I would have done a little smaller. Because for me it's about the interaction. To manipulate it by hand if it gets too big, then it get difficult to do rotations at the same time. If I wanted to show the combination of translations and rotations then it will get difficult.”

Colin Scholler: “Any other feedback, both positive and negative?”

Vartan Kurtcuoglu: “You used rubber bands so you didn’t have a specific stiffness in mind that you wanted to achieve.”

Nazanin Beigi: “Do you think there’s a better way to show the synovial joints?”

Vartan Kurtcuoglu: “If I try to think like a second year medical student who would see this then I would not know how much freedom I have really. Of course I can do a rotation but is this translation okay? Is this normal? Is it a normal mode or is it part of your model? I would think it's important to not allow for movement where in reality there is also no movement. So that you don't have something in your mind that does not correspond to reality. Also, when it comes to the different modes of oscillations, displacements are rather small. Here you can principally have very large displacements. That would also be something I would think would be helpful if the displacements about what you would expect scaled up from reality.”

Nazanin Beigi: “Do you think this model makes it easy to show abnormalities?”

Vartan Kurtcuoglu: “It depends for what type. For anatomic ones, sure. If you have just the regular reference and then you can see. I think abnormalities would really help if you can show what the physiologic implications are. If you have a restriction of movement then you can show that but that would require that your normal physiologic one does not move more or less than what you would have in the real system.”

Nazanin Beigi: “Is there anything major you think is missing that we should have added?”

Vartan Kurtcuoglu: “With the frame then the context will come. If you add the frame and then give location on where we are in the middle ear that would be helpful. Otherwise, for someone who is not aware or does not know the anatomy. The reference is extremely important.”

Nazanin Beigi: “In general do find this a useful model for a classroom environment?”

Vartan Kurtcuoglu: “I think it has potential. In the current form I don't think I would use it because it doesn't add to what we already have in terms of the anatomic structures. I mentioned those are smaller so they're to scale. But, I see where you want to go and I think that's a good idea.”

Appendix K: Interview Manuscript; Simulation Lab

The interviewee has asked to remain anonymous. The interview was conducted electronically over email.

Consent Script

Our names are Nazanin Beigi, Colin Scholler, Dan Seeley, and Sarah Vazquez and we are students from Worcester Polytechnic Institute working on a 7 week research project on otology education involving basic physics applications. Our research team is sponsored by the UniversitätsSpital Zürich to develop better teaching models for graduate students. We would like to invite you to talk with us about your knowledge of biomedical models and how to create them. The interview should only take between 20 to 30 minutes.

The purpose behind this interview is to assess your experience with modeling in regards to otology and other models used within the field of study. The information from this interview can be chosen to remain anonymous if desired. At the end of our project, this paper will be published through WPI's library system.

The interview is completely voluntary. You can choose to not answer any question that you don't want to answer and stop participation at any time. Before we begin, I will ask you some questions about permission:

- Do you agree to be a part of this interview?
  - Yes, I do.
- Would you like to remain anonymous?
  - Yes, I would.
- Would you be comfortable with us voice recording the interview? As mentioned in previous correspondence via email.

        - Yes, I would.
    - Do you have any questions before we begin?
        - No, I don't.

Interview Protocol - Modeling

- What research does your applied biomechanics lab specialize in?
    - Bone conduction using a 3D finite element model of human head including auditory periphery
- What are some of the current research projects you are a part of?
    - Development of personalized middle-ear FE model based on the CT images
    - Development of physical head model including auditory periphery for better understanding of bone conduction
- What models or simulations has your lab created regarding the ear?
    - 3-dimensional finite element model of the middle ear, cochlea, and human head based on real geometry
- How are your models different from static anatomical models?
    - Since our model is a computational model, we can simulate various cases with various conditions which is impossible in the static anatomical model.
- Did you use any software programs to create these models? If so, which programs?
    - Yes. For the pre-processing, we've used intrinsic software in vivaCT 40, Hypermesh, and MATLAB. For the analysis, we are using ACTRAN.
- What were some challenges when creating the models?

    - Segmentation from CT images. It was really difficult to distinguish each component from various ones due to vague boundaries among components in the images.
- How did you overcome these challenges?
    - Keep discussing with clinical doctor to confirm if the component was segmented properly.
    - Special fluid was inserted into the cochlea to distinguish basilar membrane in the CT images.
- What are the advantages and disadvantages of simulated models compared to physical models?
    - The advantage of the model is that we can simulate any case even if it is impossible in reality.
    - The disadvantage is that it is difficult to show the credibility of the simulation results unless we validate the model properly.
- Did your background in mechanical engineering and physics help your understanding when studying hearing mechanics?
    - Yes, it did. Knowledge for mechanics is helpful for me to develop and modify the model, and to analyze the simulation results properly.
- What are some important factors to keep in mind when modeling the mechanics of hearing?
    - Validation of model
    - Whether the mechanical properties of each component are in reasonable ranges

    - Boundary condition is properly applied to the model in order to simulate the case in which I am interested

Interview Protocol - Teaching (If Applicable)

- Which courses do you currently teach?
    - Solid mechanics, Acoustics, Engineering mathematics
- What types of teaching methods do you use when teaching graduate students?
    - Lecture
- What types of electronic resources do you use such as PowerPoint or Google Slides?
    - PowerPoint
- Do you ever request student feedback on your teaching methods? If so, how have students reacted to your teaching, if you are willing to share that with us?
    - Yes, I do. In fact, there are two mandatory feedback requests in a semester.
- What do you know about the middle ear and the physics behind how we hear?
    - Leverage effect, impedance, etc.
- Do you believe interactive models facilitate better learning? How so?
    - Yes, I do. Students can directly see what is going on in an ear if we use the interactive model.
- Have you had any experience with interactive models? If so, please explain.
    - No, I have not yet.
- What types of models would you like to see within the classroom learning environment?
    - Virtual ear. If technology is fully developed later, I want to see the model from which I can feel the tactile impression of each component.

Appendix L: Interview Manuscript; (Anonymous)

The interviewee has asked to remain anonymous and declined audio recording.

During this interview, the interviewee expressed how the project they have been working on has to do with bone conduction. They focus on the different angles that sound is picked up on and travels to the ear and through the canal. The research has been using hearing aids and placing it on different parts of the bone behind the ear, to try and improve hearing loss. The interviewee expressed how they are a physics major and received her bachelors and masters in physics. In addition, when asked about whether or not they found physical models more useful or digital, the interviewee expressed that a digital model is more beneficial. They are a visual learner, and believed that a digital model would be better because it is easily portable and you can have it within any given moment that you need it to look at it. When asked about their background, the interviewee explained how easy it was for them to work on the project as their physics background gave them a better insight to their work. Others, while they did not struggle, simply did not have the same background as the interviewee did.

Appendix M: Biology of Ear

Tympanic Membrane (Further detail): The outer portion of the tympanic membrane is exposed to the atmospheric pressure, specifically through the auditory tube, such that the tympanic cavity (the cavity in which it is located) is continuous with the cells in the jaw and throat area (Alberti, 2004). Usually the auditory tube is closed, however, when swallowing, yawning or chewing, it pulls the tube open, allowing air to travel in or out of the tympanic cavity. This opening of the tube allows the pressure of the air within the middle ear to equilibrate with atmospheric pressure, allowing the pressure of the tympanic membrane to become equal on both sides. If there is excessive pressure present on the tympanic membrane, it reduces hearing senses as it does not allow the membrane to vibrate freely. This is often experienced in an airplane during altitude changes. At higher altitudes, your ears feel blocked. This is due to the change in pressure outside the ear while the pressure inside the ear remains constant. Yawning or swallowing in this instance opens up the auditory tube, allowing the pressure on both sides of the tympanic membrane to equalize, relieving the pressure distortion as the eardrum “pops” back into place. As the external pressure changes, the tympanic membrane bulges since the pressure within the middle ear remains the same potentially resulting in a painful sensation

Eustachian tube: This is a canal that links the middle ear with the back of the nose (Alberti, 2004). The Eustachian tube helps equalize the pressure in the middle ear for the proper transfer of sound waves. The outer wall of the tympanic cavity is the tympanic membrane; the inner wall is the cochlea. The upper area of the tympanic cavity forms the lower bone of the middle lobe of the brain and covers the jugular bulb. The beginning of the middle ear presents the opening of the Eustachian tube and by its posterior end there is a path to a cluster of air filled cavities within the temporal bone known as the mastoid air cells. The middle ear extends the necessary access to the respiratory air spaces of the nose and the sinuses. It is also lined with respiratory membrane, just like the inside of the nose and throat, which is very thick near the start of the eustachian tube and becomes gradually thinner as it begins to pass into the mastoid cells. As the tube begins to leave the ear, it builds most of its support off of bones. However, as it nears the back end of the nose, it consists of cartilage and muscle. This allows muscles to actively open the tube and allowing the air pressure in the middle ear and the nose to equalize.

Biological component - Further detail on TMHS: TMHS plays a role in a molecular complex called the tip link, which was discovered to cap the stereocilia protruding out of hair cells (Staff, 2012). These tip links connect the tops of neighboring stereocilia and bundle them together. Without these the hair cells become splayed apart. Additionally the tip links also house some of the components crucial for hearing including the proteins that physically receive the force of a sound wave and transduce it into electrical impulses by regulating the activity of ion channels.

External (outer) ear – The outer ear helps act as a funnel to send incoming air vibrations to the eardrum (Alberti, 2004). The outer ear is responsible for determining the sound location due its intensity and the identification of the ear receiving the sounds.

- **Pinna (auricle)** – The pinna is the outer cartilage portion of the ear (Alberti, 2004). Our pinna collects the vibrations and sound waves and directs them to the external ear canal via patterns known as whorls and recesses allowing us to determine if the sound wave from in front or behind the head.

External auditory canal (tube) – The external canal is a connecting tube from the outer ear to the middle ear (Alberti, 2004). This tube is approximately 4 centimeters long and forms an “S” shape. The opening of the canal is supported by cartilage, the remainder of the length is supported by bones. Skin lines the canal and produces earwax through sweat glands that combine with dead cells. Earwax and fine hairs guard the entrance to the ear canal, together, preventing any particles reaching the inner ear canal and injuring the eardrum.

Middle ear (tympanic cavity)

- **Ossicles** – These are the three small bones connected in the inner ear which transmit sound waves from the tympanic membrane to the inner ear (Alberti, 2004). The bones are called malleus, incus, and stapes (hammer, anvil, and stirrup), respectively.
  - The malleus is connected to the eardrum. This bone has a handle attached to the inner surface of the eardrum and a head suspended from the wall of the tympanic cavity.
  - The incus is connected to the malleus on the side closer to the eardrum and the stapes on the side closer to the inner ear.
  - The stapes has an arch and a footplate. This footplate is held by ring-like tissue in an opening called the oval window; the entrance into the inner ear.

Inner ear – This is one of the deepest parts of the ear (Alberti, 2004). It is located within the bony labyrinth, which incorporates a maze of bone paths that are lined by the membranous labyrinth. Throughout the inner ear, there is a chamber known as the vestibule which is important when it comes to balance.

- **Cochlea** – This part of the ear is responsible for containing the necessary nerves for hearing. The organ of hearing refers to the vestibule stemming from the cochlea allowing for sound vibrations to be perceived. Due to the cochlea's spiral shape, its length easily fits within the narrow cavity of the inner ear. In width, the cochlea is about 9 millimeters at the base and 5 millimeters high. It spirals itself around a section of spongy bone known as the modiolus. This bone is shaped like a screw with the threads forming a spiral platform that eventually supports the cochlea.

- **Semicircular canals** – These contain receptors for balance. The canals are three semicircular, interconnected channels located in the inner ear. These canals are known as the horizontal, superior, and posterior canals. Each canal is filled with endolymph, which contains motion sensors within the fluid.
  - The horizontal canal is the shortest canal. The movement of fluid within this canal relates specifically to the rotation of the head around a vertical axis. It is at a 30-degree angle from the horizontal plane.
  - The superior canal is part of the vestibular system and detects rotations of the head in around the lateral axis.
  - The posterior canal is part of the vestibular system as well and detects rotation of the head around the frontal axis, also known as the coronal plane.

Appendix P: Dysfunctions within the ear

Dysfunctions in the ear can happen anywhere, one of them being the inner ear. Sensorineural Hearing Loss results from damage to the small sensory cells in the inner ear, called hair cells (Gorbach, 2004). The damage can occur as a result of disease, aging, or injury from noise or certain medicines. For example, a very common noise-induced injury is known as NIHL, or noise-induced hearing loss. The injury comes from constant loud noise, such as live concerts. These injuries lead to other disorders such as Tinnitus, a constant ringing within the ear even though there is no actual sound present. Tinnitus ends up worsening from taking medications such as aspirin. This evidence shows how a simple injury from extreme noise has a ripple effect on an individual, with the capability continued damage via everyday medications. Surviving hair cells detect the larger vibrations and convert them into neural signals that are passed along to the brain. Greater damage to one's hair cells directly leads to more severe hearing loss. This results in higher amplification needed to properly hear sound. However, there are practical limits to the amount of amplification a hearing aid can provide. For example, if the inner ear is too damaged, even large vibrations will not be converted into neural signals. Many believe that a traumatic impact to the temporal lobe, where the auditory cortex is, would lead to hearing problems and cause deficiencies (Packer, 2015). However, there has been no evidence of such occurrence. In fact, scientists have found that ear damage has led to brain dysfunction instead.

Appendix Q: Wave Types vs. Sound

A standing wave is a vibrational pattern that is created when two waves with the same amplitude and frequency moving in opposite directions collide. Standing waves result from the interference of two waves. When the waves are superimposed, the energy created is either added or cancelled out. Waves moving in opposite direction produce an oscillating wave that is fixed in space. Due to interference, specific points along the medium appear to be still, known as a standing wave pattern. Within a standing wave pattern are points known as nodes and antinodes. The nodes undergo the minimum displacement within a vibration cycle, while the antinodes undergo the maximum displacement within a vibration cycle.

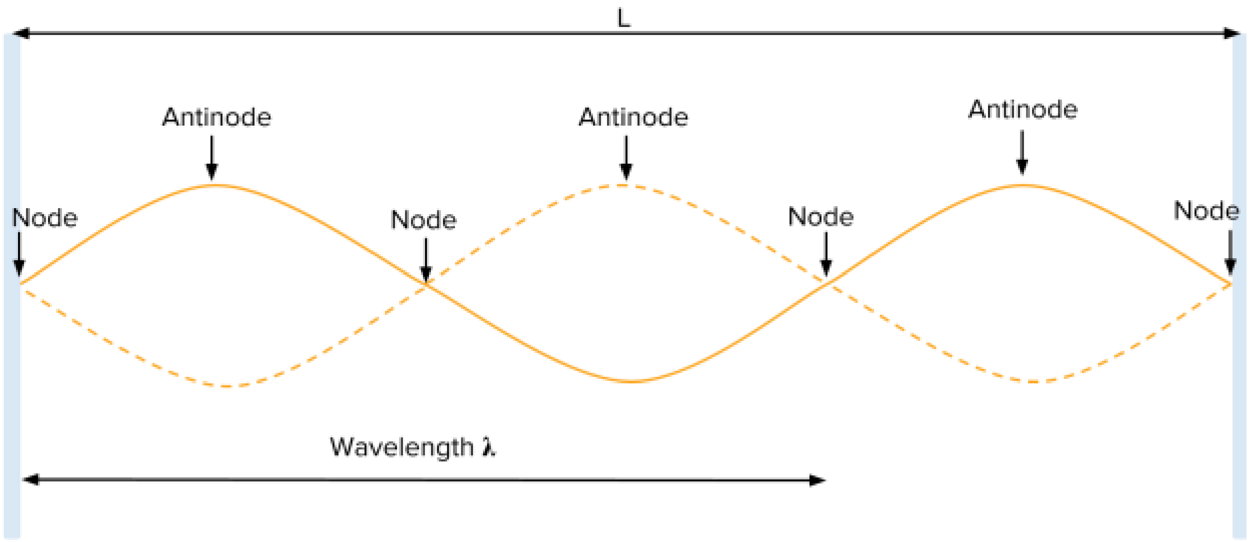


Figure N.1 Nodes and Antinodes. (Source: Standing Waves Review, Khan Academy, 2019)

Antinodes and nodes are points, rather than actual parts of the wave, that remain in the same location (Henderson, 2001). The nodes and antinodes are simply unique points on the medium that make up the wave pattern.

A vibration within a tube would ultimately create a standing wave as the wave ends up reflecting off the end of the tube, ultimately interfering with itself (Henderson, 2001). When blowing into a brass instrument, sound is created but only the sound waves that fit in the tube will resonate, other frequencies will be lost. The longest wave that resonates is known as the fundamental. The other waves are known as the overtones.

Another example is that standing waves occurs when a wavelength matches the distance between two walls of a room (Henderson, 2001). A specific frequency will fit between the surfaces. The reflection off the wall strengthens the initial wave as long as the reflections remain in phase

For transverse waves, the best way to understand how sound is created is through the example of a violin. If a violin string is bowed or plucked, the vibrations are also formed in a standing wave pattern. The nodes will be at the fixed ends, and an antinode within the center. Several harmonics are also produced as well. A visual representation is shown below.

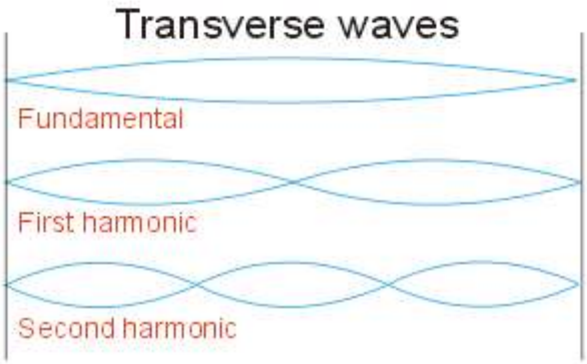


Figure N.2 Transverse Waves. (Source: Hollis, 1999)

Another wave type is known as the mechanical wave. This wave portrays a disturbance created when a vibration travels through a medium from one location to another. The energy is transported through the movement of the medium. The mechanical wave propagates itself through a medium by particle interaction. One particle creates a push or pull on its neighboring particles, which then leads to a displacement of that neighbor from the equilibrium or rest position. This pattern continues to move until another wave is encountered to disrupt it or a boundary with another medium. Since a sound wave is a disturbance that is transported through a medium via the mechanism of particle-to-particle interaction, a sound wave is characterized as a mechanical wave (Elert, 2019).

Displacements are combined vectorially, however, usually vibrations or oscillations are on a single plane, so the displacements would be added algebraically. “The principle depends on the medium behaving linearly when the waves pass through; i.e. when the parts of the medium have twice the displacement, it has twice the restoring force”(Isaac Physics, 2014 pg.2). For very large amplitudes this breaks down and harmonics are obtained. Once the point of intersection is passed by the waves, they are completely unchanged as they separate out again; unless the medium has been overstretched. When superposition occurs for slow mechanical waves, observations can be made on the amplitude. For high frequency waves, such as, the intensity is measured as the energy of the wave in the region. The resulting intensity at the point of intersection can be greater or smaller than the intensity due to each of the superposing waves. Superposition is important for explaining phenomena such as interference, diffraction, and standing waves.

Superposition in relation to sound waves is important due to amplitude. However, it depends on whether it is constructive interference or destructive interference. Constructive interference is when two waves superimpose and the resulting wave has a higher amplitude than the previous waves. Destructive interference is when two waves superimpose and cancel each other out, leading to a lower amplitude.

Amplitude is crucial for hearing as it determines the loudness or volume of the sound. A higher amplitude correlates to a louder sound. A smaller amplitude correlates to a softer sound. Vibration plays an important part in amplitude as well. Since it transmits energy into the medium through the vibrational pressure. The more energetic the vibration is, the larger the amplitude as molecules tend to move back and forth more vigorously. Thus, creating a louder sound.

The sensitivity of the ear in relation to these sound waves is also important. The human ear can handle some frequencies better than others. The volume the ear receives depends on amplitude and frequency as a whole and whether that frequency lies in a region for which the ear is more or less sensitive.

Appendix R: Review of Otology Education

Otology education can be improved in three areas, which are medical school education, physicians' residencies post medical school, and in the continuation of medical education (Hu & Meyer, 2012). Several studies have examined the otolaryngology training in graduate medical education and postgraduate medical education. They have found that it has been 45% more effective than trying to approach otology through online modules and separating the branch from medical education overall.

Harvard Medical School (HMS) is one of the few schools that has a branch dedicated to otolaryngology (Hu & Meyer, 2012). Harvard offers otolaryngology training at various levels, including residency training through the HMS Otolaryngology Residency Program, clinical fellowships, research fellowships and postdoctoral training, as well as medical student education and sub-internships.

As specialists realized that there is a need for improved otology education, new programs have been established (Sheehy, 2002). For example, the House Ear Institute developed a clinical fellowship program that focused on educating the leaders of otology and neurology in the United States. House Clinic and House Ear Institute has been one of the top choices for otolaryngologists across the United States to pursue advanced fellowship training in the fields of otology and neurology. Although the fellowship program has been around since 1947, it did not fully develop and become a successful program until 2000.

Appendix S: Otology on a Global Scale

The European and U.S. medical education programs differ in many ways, including the field of otology. Otology has seen many developments in the use of simulators for teaching and training (Javia, 2012). There are many models and simulators ranging from simple real models for training in otoscopy to virtual simulators for temporal bone dissection. Within Asia, the approach to teaching otology follows very specific active models through simulation training. There are currently various models made available that have been aiming to provide a very realistic demonstrative model. These models include the use of cadavers, employing an array of preservation techniques, to virtual reality simulators. There currently is an attempt being made to create a completely realistic anatomical model of the ear, developed by Martyn Cooke and his team at the Royal College of Surgeons (Nogueira & Cruz, 2010). Additionally, an advanced Japanese model is used for teaching otoscopy in some international centers. This highly regulated developed model provides training and numerous possibilities with concepts such as tympanic membrane perforation, cholesteatoma, sinuous outer ear canals, and tympanic glomus. This model is used in developed countries where few patients exist that have ontological conditions. It has a fixed unit, composed of an outer ear canal and middle ear that can be exchanged and examined indefinitely, along with a mobile head.