Post-Auricular Orientation of Auditory Attention in Sound Field versus Virtual Sound Space

by

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Abstract

Background: The post-auricular muscle in many species changes the orientation of the external ears to improve hearing for biologically relevant sounds. The same muscle exists in humans and is modulated by sound, but humans cannot similarly change the direction of their ears. The objective of this current project focused on measuring the activity of the post-auricular muscle during a speech-in-noise listening task where the orientations of the speaker and the noise were controlled experimentally. This was done in order to determine how the signal-to-noise ratio of the post-auricular muscle varies as a function of presentation mode (actual sound space versus virtual auditory space) and azimuth (target speech and noise co-localized at 45° and target speech and noise spatially separated at 135° and 45°, respectively. It was hypothesized that post-auricular muscle activity would be reliably recorded in approximately two-thirds of all participants, that post-auricular muscle activity would be elicited in the same proportion of subjects when evoked via earphones in a virtual sound space as compared to when it is evoked from speakers in real space, that there would be no significant differences in the magnitude of post-auricular muscle activity between these conditions, and that the maximum muscle engagement would be observed with speech presented at 135° and noise presented at 45°.

Methods: Muscle activity was recorded with four electrodes affixed around the ears (behind the pinna and in posterior, anterior and superior positions) as well as on the outer canthi (to track ocular activity), and lateral neck (to track any tension in the neck) while listeners completed a spatialized listening test in which the source locations of the target speaker and competing noise were controlled experimentally in both soundfield and in a virtual auditory space.

Results: The post-auricular muscle response was shown to be reliably recorded across all participants within the study. There was a significant main effect of channel and a significant interaction between presentation mode and channel. There were no significant differences between presentation modes for any other muscle. Further, it was shown that there was no significant effect of azimuth to be found.

Conclusions: This study provides evidence for reliable post-auricular muscle activation across all participants, as it was shown that all participants engaged the post-auricular muscle in a speech-in-noise task. This activity sometimes co-occurred with activity of the anterior-auricular muscle and to a lesser degree, the neck and ocular muscles. Further, it was found that this activity was highly variable across subjects, with some subjects engaging the muscle more for speech presented at 45° and some engaging the muscle for speech presented at 135°. Importantly, there was no significant difference in the amount of muscle engagement between conditions in which sound was presented in the sound field and in which sound was presented in a virtual sound space. The engagement in virtual sound space suggest that post-auricular muscle activation occurs as a consequence of spatially directed attention, even when changes in pinna orientation are unlikely to have any effect on the sound that is heard.

List of Abbreviations Used

AAM: anterior auricular muscle
ABR: auditory brainstem responses
ANOVA: Analysis of Variance
BATS: Biosemi Active Two EMG measurement system
CON: contralateral electrode
CRM: Coordinate Response Measure
dB: decibel
dBHL: decibels in hearing level
EEG: electroencephalogram
EMG: electromyography
EOG: electrooculography
EW: ear-wigglers
HRTF: head related transfer function
Hz: Hertz
ILD: interaural level differences
ITD: interaural time differences
MATLAB: Matrix Laboratory
NEW: non-ear-wigglers
OCC: outer canthi electrode
PAM: postauricular muscle
PAMR: postauricular muscle response
RMS: root mean squared
SAM: superior auricular muscle
SCM: sternocleidomastoid
sEMG: surface electromyography
SNR: signal-to-noise ratio
SPL: sound pressure level
SPSS: Statistical Package for the Social Sciences
TAM: transverse auricular muscle
VEMP: vestibular evoked myogenic potential

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Chapter 1

Introduction

1.1 Background

The post-auricular muscle (PAM) in many species changes the orientation of the pinnae to focus on biologically relevant sounds. This muscle exists in humans and is modulated by sound; however, we do not make ear movements when we focus our attention to try and hear something better. Given the inability to similarly orient our pinnae, this muscle is considered to be vestigial in humans. Recent evidence suggests that this muscle is activated during tasks that involve listening in noise distributed in virtual space and in the soundfield independent of one another; however, it is not known whether these give rise to similar levels of activation. This question is of interest since it may be possible to use measures of post-auricular muscle activation to estimate the directional focus of auditory attention and to use this information to improve listening experiences in both real and virtual spaces (e.g., with hearing aids in real spaces or earphones in virtual spaces). Thus, the present project investigated whether the post-auricular muscle response is evoked in a speech-in-noise task both in soundfield and virtual conditions, and whether they varied between these conditions.

1.1.1 Post-Auricular Muscle Activity Across Species

It is the post-auricular muscle that allows for the changes in orientation of the pinnae in many species to focus on these biologically relevant sounds. The existence of this “evolutionary fossil” in humans suggests that humans evolved from species that utilized their ears more fully to assess important, loud, or startling noises, and to express emotions like fear and rage.[1] Essentially, animals have evolved a wide range of adaptations to cope with different ecological niches and survival strategies. Among these adaptations, the movement of the ears has evolved in different animal groups for various functions such as communication, predator detection, prey detection, thermoregulation, and balance. While the majority of research on pinna movements in animals has been done in cats[2–8], there has, however, been research using other animals, including bats[9–11], elephants[12,13], and even gerbils[14].

The domestic cat is one animal that is particularly adept at controlling the movement of their ears using its post auricular muscles—enabling an independent and precise movement of their ears[4,5,7,8]. The post auricular muscles in cats are particularly essential for their hunting and survival skills. This is accomplished by the movement of the earflap via the post-auricular muscle, which allows cats to detect and locate prey more efficiently, helping them to capture sounds from different directions[4,5,7,8]. Cats can move their ears in different directions, including up, down, backward, and forward, and they can even rotate them 180 degrees, which allows them to focus on sounds that are behind them[8].

Several studies have investigated the diverse role that the superior colliculus holds with respect to a cats' sensory and motor functioning[2,3]. Two studies in particular hypothesized that in addition to the superior colliculus controlling ocular movements and visual attention, it may play a role in the control of other motor behaviours, including the movement of the pinna[2,3]. In the first study, investigators used a combination of electrical stimulation and anatomical tracing techniques to map out the pathways that connect the superior colliculus with the muscles that control the pinna in order to further investigate the anatomical connections that might exist between the superior colliculus and the muscles that control pinna movements in the cat. Their results indicated that there are indeed direct connections between the superior colliculus and the muscles that control the pinna in the cat. Specifically, they found that stimulation of certain areas of the superior colliculus led to specific movements of the pinna, suggesting a direct and specific control pathway[2].

Similarly, the second study published within this same timeframe investigated the neural mechanisms that underlie the ability of cats to orient their ears towards sound sources, and had a particular focus on the superior colliculus due to its involvement in both the generation of movements and the processing of sensory information[3]. The hypothesis that the superior colliculus may play a role in the control of the movement of the pinna was tested by researchers who recording the neural activity of cells in the superior colliculus of anesthetized cats while presenting them with auditory stimuli. They found that a subset of cells in the superior colliculus responded selectively to sounds presented from specific directions, and that the responses of these cells were associated with movements of the pinna in the corresponding direction[3]. The authors also investigated the relationship between sensory and motor signals in the superior colliculus. They found that the same cells that responded to auditory stimuli and controlled pinna movements also showed activity related to movements of other parts of the body, such as the eyes and head[3]. This suggests that the superior colliculus integrates sensory and motor information to generate coordinated movements in response to sensory input. Overall, both studies provide evidence that the superior colliculus plays an important role in the control of pinna movements in cats and sheds light on the neural mechanisms that underlie the integration of sensory and motor information in the brain.

Once the underlying motor mechanisms were more understood, the focus of feline research seemingly shifted towards that of sound localization[4,5,7,8]. One study explored how the ability to locate the source of sounds evolved in mammals in general, which involved the detection of differences in sound arrival time and intensity between the two ears[5]. Several key adaptations that allowed for the evolution of better sound localization abilities in mammals were highlighted within the article. For example, the development of the pinnae helped to capture and direct sound waves towards the ear canal, allowing for more accurate detection of sound direction[5]. From this, research honed in specifically on sound localization in cats, and the pinna movements recorded during such sound localizations. Sound localization is defined in these articles as the ability to determine the direction and distance from which a sound is coming, and it is an important skill for animals to locate potential prey or avoid predators[7]. Since pinna spectral shaping plays a role in sound localization, pinna movement may also be involved in sound localization, especially given the evidence that pinna movement is controlled by the superior colliculus, which plays an important role in sound localization in mammals. One particular study presents several experiments in which cats were trained to respond to sounds presented from different locations. The authors measured the cats' ability to localize sounds by changing the location of the sound source and observing the cats' behavioral responses, such as head or ear movements[7].

One of the key findings of the study was that cats are able to localize sounds using interaural time differences (ITDs) and interaural level differences (ILDs)[7]. ITDs are defined as the differences in the time it takes for a sound to reach each ear, and ILDs are differences in the sound intensity received by each ear. These cues can be used to determine the location of a sound source in the horizontal plane. The authors also found that cats are less accurate at localizing sounds in the vertical plane, and that the shape of the cat's head and ears may play a role in this limitation. Additionally, the study showed that cats are able to adapt to changes in the location of sound sources over time, indicating a degree of plasticity in their sound localization abilities[7].

A second article explores the mechanisms by which cats are able to localize the sources of sounds in their environment, specifically focusing on the role of the pinna in this process[8]. At the time that this was published, previous literature had shown that the cat's ability to localize sound is highly dependent on the movement of its pinnae and that such movements help to amplify and filter sound waves, thus allowing the cat to detect subtle differences in the timing and intensity of sounds arriving at its two ears[7]. The exact nature of these movements and their relationship to sound localization, however, was not well understood at that time. To investigate this phenomenon, the authors of the article recorded the movements of the pinnae in cats as they were presented with sounds from different locations. The cats were trained to perform a task that required them to turn their heads towards the location of a sound source in order to receive a reward. The researchers used high-speed video recordings to capture the movements of the cats' pinnae as they performed this task[8]. The results of the study revealed that the cats' pinnae move in a highly specific and coordinated manner in response to different sound stimuli. For example, the pinnae of cats were found to move differently depending on whether a sound was located in front of them, behind them, or to the side[8]. The researchers also found that the timing and amplitude of these pinna movements were correlated with the cats' ability to localize the source of the sound[8].

Research has also been conducted and published on frequency dependence at the pinna, specifically examining the role of the cat’s pinna in the directional amplification of sound[4]. This was done through investigating the directional amplification properties of the pinna by measuring the sound pressure level (SPL) at the ear canal for sounds coming from different directions and at different frequencies. It was found that the pinna provides directional amplification for sounds in the range of 2-10 kHz, which is the frequency range most important for localizing high-frequency sounds in space[4]. The amplification was found to be highest for sounds coming from the front and from above, and lowest for sounds coming from below. Further, investigators found that the directional amplification properties of the pinna were frequency-dependent, with the degree of amplification varying depending on the frequency of the sound[4]. Specifically, the amplification was found to be highest for sounds in the range of 4-8 kHz, with lower levels of amplification for sounds above or below this range.

Because the pinna of the cat is an intricate structure with several folds and ridges that serve to enhance the cat's ability to localize sounds in space, the researchers also examined the role of these various folds and ridges of the pinna in producing the directional amplification. They found that different structures of the pinna were responsible for amplification at different frequencies, with the concha (the bowl-shaped cavity at the base of the pinna) being most important for amplification at higher frequencies[4]. Overall, this is an important study which provides insight into the mechanisms by which the pinna of the cat provides directional amplification for sounds, and highlights the importance of frequency-dependent amplification in sound localization[4].

Lastly, research was conducted on the effects of the pinna position on the head-related transfer functions in cats. A head-related transfer function (HRTF) is a measurement of how sound waves are transformed as they travel through the head and interact with the listener's ears [6]. The pinna plays an important role in shaping the HRTF. Thus, researchers examined how different positions of the pinna affected the HRTF in cats. One study in particular used seven anesthetized cats and measured their HRTFs using a microphone inserted into the ear canal[6]. The researchers varied the position of the pinna in four different ways: straight ahead (the control position), rotated forward, rotated backward, and rotated outward. The researchers then analyzed the data to determine how the different pinna positions affected the HRTF.

The results showed that the position of the pinna had a significant effect on the HRTF. When the pinna was rotated forward or backward, the peak frequency of the HRTF shifted upward or downward, respectively. When the pinna was rotated outward, the HRTF was generally weaker, and the peaks were less pronounced[6]. The researchers also found that the changes in the HRTF were not uniform across all frequencies. At low frequencies, the HRTF was relatively unaffected by the pinna position. However, at higher frequencies, the changes in the HRTF were more pronounced[6].

The study has several important implications. First, it shows that the position of the pinna can significantly affect the way that sound is perceived by the listener[6]. This has important implications for the design of hearing aids and other devices that rely on HRTFs to create a realistic sound environment. Second, the study provides insight into how the auditory system processes spatial information[6]. The HRTF is an important cue for localizing sound sources in the environment. By understanding how the pinna affects the HRTF, researchers can gain a better understanding of how the auditory system processes spatial information.

Bats, on the other hand, use their post auricular muscles to control the movement of their ears in order to navigate and hunt in the dark[9–11]. Bats are nocturnal animals that rely on echolocation to locate their prey, and such echolocation allows bats to localize sound sources in three-dimensional space[9–11]. Echolocating bats emit high-frequency sounds known as ultrasonic vocalizations, and listen to the echoes that bounce off objects in their environment and return to their ears[9]. They use the timing and frequency of these echoes to analyze the sound waves and thus determine not only the distance and direction of objects in their environment, but bats can also determine the size and shape of such objects, including their prey[9]. Essentially, by analyzing the echoes, bats can create a mental image of their surroundings[10]. However, it has been unclear how bats are able to localize objects in three dimensions, especially when objects are at different elevations.

One group conducted research on two species of echolocating bats, the big brown bat and the mustached bat, and found that the bats use a combination of different auditory cues to localize sound sources in three dimensions[9]. These cues include the timing and frequency of echoes, as well as the differences in sound level and spectrum between the two ears. The researchers also found that the bats are able to use the relative intensity of echoes at different frequencies to determine the elevation of objects in their environment. They suggest that this ability may be related to the shape of the bats' ears, which are designed to enhance certain frequency ranges. Thus, to control the shape of their ears helps them to direct and focus the incoming sound waves more effectively. For example, when a bat emits a high-frequency sound, the sound waves hit the object and bounce back. The bat's ear receives the returning waves, and the post auricular muscles control the movement of the earflap, enabling the bat to focus on the sound and locate its prey more accurately. According to this study, bats are able to move their ears in a way that allows them to better localize sounds in their environment. The researchers found that the post auricular muscles in bats are able to move the pinna in a variety of directions, including up and down, forward and backward, and even in a circular motion[9].

One aspect of echolocation that is critical for bats is the Doppler effect[10]. This is the phenomenon where the frequency of a sound wave appears to change as the source of the sound moves relative to the observer[10]. For example, if a bat is flying towards an object, the frequency of the soundwave that bounces back from the object will be higher than the frequency of the sound wave that was emitted by the bat. If the bat is flying away from the object, the frequency of the sound wave that bounces back will be lower. In a study which focused on how bats use Doppler shifts to extract information about their environment, it was found that the ears of bats are uniquely adapted to detect these shifts with high precision[10]. The researchers used high-speed cameras to study the movements of the ears of three species of bats as they flew in a wind tunnel. They found that the ears of the bats move rapidly and independently of each other, which allows them to detect even the slightest changes in the frequency of incoming sound waves. The researchers also found that the shape of the pinna plays a crucial role in detecting Doppler shifts[10]. As aforementioned, the pinna acts as a filter that enhances certain frequencies of sound while suppressing others. This allows the bat to focus on the specific frequencies that are most informative for their echolocation.

When looking at more specific species of echolocating bats, it was found that the Horseshoe bat and Old World leaf-nosed bat have two discrete types of pinna motions[11]. Previous studies have shown that the pinna of bats can move in a variety of ways to help them capture and process sounds from their environment. However, the authors of this study noticed that the pinna motions of horseshoe bats and Old World leaf-nosed bats seemed to fall into two distinct categories. To investigate this phenomenon, the researchers studied the pinna motions of six species of horseshoe bats and six species of Old World leaf-nosed bats using high-speed video recordings. They found that both groups of bats had two distinct types of pinna motions, which they called "type I" and "type II."[11].

Type I pinna motions involve the rotation of the entire pinna around its base. In horseshoe bats, this motion is achieved by contracting a muscle called the auricularis superior. In Old World leaf-nosed bats, it is achieved by the contraction of a muscle called the paratragicus. Type I motions were observed in all six species of horseshoe bats and four of the six species of Old World leaf-nosed bats. Type II pinna motions, on the other hand, involve the folding and unfolding of the pinna along a horizontal axis. This motion is achieved in horseshoe bats by the contraction of a muscle called the auricularis anterior. In Old World leaf-nosed bats, it is achieved by the contraction of a muscle called the transversus auriculae. Type II motions were observed in four of the six species of horseshoe bats and all six species of Old World leaf-nosed bats.

The authors suggest that the two types of pinna motions may be related to the different environments in which horseshoe bats and Old World leaf-nosed bats live. Horseshoe bats are typically found in cluttered environments, such as caves or dense vegetation, where they may need to filter out unwanted echoes from their sonar signals. Type II pinna motions may help them do this by directing sound waves toward the ear canal while blocking echoes from other directions. Old World leaf-nosed bats, on the other hand, are typically found in open habitats, such as savannas or forests, where they may need to detect prey over long distances. Type I pinna motions may help them do this by increasing the overall sensitivity of the ear to sounds.

This study is important, as it demonstrates that bats have two distinct types of pinna motions, which may be related to their different ecological niches. This finding adds to our understanding of the diversity of bat hearing mechanisms and could have implications for the design of sound localization and filtering.

Elephants, too, are known for their ability to move their ears using their post auricular muscles. In the late 1800s, a photographer used high-speed photography to capture the movements of an elephant's ears as it walked. From this, it was found that the elephant was able to move its ears in a variety of ways, including forward and backward, up and down, and even in a figure-eight motion[12]. Further studies have since examined how these motions can be used as a form of communication with other elephants. For example, when an elephant is angry or aggressive, it will hold its ears out to the side, making it look bigger and more intimidating. Conversely, when an elephant is relaxed, it will hold its ears forward or backward, depending on its mood[13]. The authors also note that elephants may use fanning movements in particular to communicate with one another or to signal such aggression or submission, as this fanning movement is highly visible and can be seen from a distance[13].

With the help of the post-auricular muscle, elephants also use their ears to regulate their body temperature. The authors note that in addition to the fanning motion, the elephant's pinnae are capable of a range of other movements, including flapping and folding, and that these movements may be used by an elephant to cool itself down in hot weather, as the movement increases the airflow over the skin of the pinnae and enhances evaporative cooling[13]. The authors also explore the potential role of the elephant's pinnae in thermoregulation and in protecting the animal's sensitive skin from the sun, suggesting that the elephant may use the pinnae to shade its eyes and face from the sun, or to cover its neck and shoulders to protect them from direct sunlight[13].

The article also discusses the role of the elephant's pinnae in hearing and sound localization. The authors note that the elephant's pinnae are shaped in such a way that they can effectively capture and funnel sound waves towards the ear canal. Additionally, it was suggested that the elephant may use movements of the pinnae to help determine the direction of sounds, as moving the pinnae can alter the timing and intensity of the sound arriving at each ear, which can help the animal locate the source of the sound[13].

Lastly, research has been done investigating how the movements of the pinnae are related to the intensity of auditory stimuli in gerbils. A study was conducted on six adult Mongolian gerbils that were individually housed and trained to sit quietly in a custom-made apparatus[14]. The apparatus consisted of a clear plexiglass tube with two small holes in the side to allow access to the ears. The gerbils were trained to remain still and wait for a reward while auditory stimuli were presented. The auditory stimuli were presented through earphones and consisted of pure tones at different frequencies and intensities. The intensity of the stimuli was varied from 10 to 70 dB SPL (sound pressure level) in 10 dB increments. The pinnae movements were recorded using a video camera that was positioned to capture a side view of the head[14].

The results showed that as the intensity of the auditory stimuli increased, the amplitude and velocity of the pinnae movements also increased[14]. This suggests that similar to cats, the movements of the pinnae are related to the intensity of auditory stimuli in gerbils. The authors suggest that the pinnae movements may serve to enhance the detection of auditory stimuli by altering the direction and intensity of sound waves entering the ear canal, and that these movements may also serve to reduce the effect of external noise on the detection of auditory stimuli.[14]

1.1.2 The Post-Auricular Muscle in Humans: Non-Auditory Tasks

Whilst there is a fair amount of literature on the mechanisms and functions of pinna movements in animals, there is seemingly very little documented with respect to humans—likely due to the fact that the muscle responsible for this movement, the post-auricular muscle, is known to be vestigial in humans. In saying this, more recent research has begun to highlight the plausible roles that the post-auricular muscle could hold in non-auditory tasks. For example, such research has shown that there could be successful control of movement in a computer game from the post-auricular muscles in a group of ten individuals, with six of the ten successfully completing the task, and two out of ten partially completing the task.[15] This was accomplished by placing electrodes on the skin over the superior and posterior auricular muscles of the ears. Surface electromyography (sEMG), a technique in which electrodes are placed on (not into) the skin overlying a muscle to detect the electrical activity of the muscle, was recorded through the Biosemi Active Two EMG measurement system (BATS). An algorithm was then used to identify an activation in the muscles, and to transform the complex coordination patterns from the activated target muscle regions into cursor control during the computer games.

These computer games were played while the participant wore a headset system that contained the multi-channel non-invasive sEMG measurement system, whereby the sEMG electrodes mounted on the headset were placed on the skin over the anterior and posterior auricular muscles. This recorded any signals that were elicited from the muscle using application-specific software. The three games required an increasing level of skill, varying from basic to high. Level of skill was measured by one's ability to switch control of the PAM from side to side, to isolate and coordinate activation of two PAMs and two SAMs, and to selectively activate each of the four muscles independently of the others during the three games respectively. This not only demonstrates that the muscle can be activated, but also that participants were able to learn and demonstrate functional voluntary control of the vestigial PAMs.[15]

In a similar study regarding the magnitude of the post-auricular muscle response (PAMR) during a non-auditory based task, participants participated in a task to steer a wheelchair using their PAMs.[16] The overall purpose of the study was to provide mobility solutions for individuals with tetraplegia. Although novel experimental control systems that are operated with the tongue or by sniffing are promising, these still interfere with other activities. Thus, a novel myoelectric auricular control system (ACS) is presented, which is based on bilateral activation of the posterior auricular muscles (PAMs) and aims to overcome the limitations of the aforementioned pre-existing control devices. In order to activate both PAMs to be able to use the ACS, a training procedure was implemented, consisting of various computer games designed to not only keep subjects motivated, but to train lateralized PAM activation. Such examples include a car racing game where subjects had to keep a car on a moving track with right or left PAM contractions, as well as a Tetris-style game whereby subjects had to move pieces left or right (with the PAM on the ipsilateral side) or rotate the pieces (through co-activation of the PAM). The efficacy of training was evaluated through analyzing how well participants could steer a wheelchair, first virtually, and then using an electric wheelchair after the training was complete.

In order to accomplish this steering, raw EMG-signals were recorded from the right and left post-auricular muscles and were collected and wirelessly transmitted from the Microcontroller Unit Tx (Sender) to the receiver (Microcontroller Unit Rx) which was attached to a computer. Rectification and low-pass filtering occurred in order to normalize the signals, conditioning them into control signals. Such output signals were then transmitted to the wheelchair. If both signals were equally strong, the wheelchair is propelled forward. Further, if for example the right PAM response was to be stronger than the left PAM response, a turn towards the right would be initiated with simultaneous forward movement. The degree to which this forward movement occurred was dependent on the strength of the PAM co-activation.

Ten able-bodied subjects and two individuals with tetraplegia were trained to activate PAMs over four days. While half could not voluntarily activate their muscles initially, all subjects were able to control the ACS and steer an electric wheelchair in a virtual obstacle course successfully after the training period. These results not only demonstrate that the ACS is a realistic alternative to current assistive technologies due to its ability to not interfere with oral communication, stability, and proportional and continuous signal generation, but that the PAM can be assigned a new function—it shows that the PAM can elicit responses to complete non-auditory tasks, doing so both bilaterally and unilaterally, and that individuals can be trained to activate the muscle to elicit responses over time.

1.1.3 The Post-Auricular Muscle in Humans: Auditory Tasks

Despite the current research surrounding this muscular response during non-auditory tasks, there was no literature stating whether the PAM has been shown to elicit a response during an auditory orienting task until 2020. The PAM was shown to elicit a response during auditory orienting tasks in two separate instances—one through a study which was conducted by Strauss et al. 2020, and the second in a study as my undergraduate thesis research.

Strauss et al. 2020 conducted experiments to study the relationship between vestigial movements of muscles around the ear and the direction of sounds a person is paying attention to[17]. In one task, exogenous attention was examined as participants tried to read a boring text while surprising or distracting sounds were played. In a second task, participants listened to a preferred podcast while a second podcast played from a different direction—allowing for endogenous attention to be measured. In both tasks, there were four loudspeakers which were fixed at +30˚, +120˚, -120˚, and -30˚. These speakers presented the novel sounds or podcasts for experiment 1 and 2, respectively. Because the interest was in the interactive role of distinct muscles in their attempt to point the pinnae in a given direction, EMG was recorded from the PAM, AAM, SAM, and TAM. Thus, for both tasks, the electrical activity in their ear muscles was recorded and revealed tiny involuntary muscular contractions towards the direction of the sound the person was paying attention to—the majority of which was recorded from the PAM.

This study also discussed alternative explanations for the auriculomotor activity observed in the two experiments. One hypothesis was that participants shifted their gaze towards the attended source, which triggered the Wilson's phenomenon, that is auriculomotor activity secondary to large gaze shifts. This was tested by analyzing the horizontal electrooculogram (EOG) and found to be absent. Another hypothesis was that participants oriented their heads towards the attended sound, but this was also found to be unlikely as there was an electrode on the sternocleidomastoid which found neck movements to be rare and small. The pattern of lateralization also supports the idea that the observed auricular responses were not secondary to eye movements or head rotations. The authors note the possibility of subtle, covert activation of head turning muscles being related to the orienting responses. Overall, the results not only suggest that auricular muscle movements indicate the direction of sounds a person is attempting to listen to, but also that these movements could be used to develop better hearing aids that can amplify the sounds a person is focusing on and minimize other sounds.

It was during my undergraduate degree that I began researching the PAM and its potential in auditory orienting tasks. The objective of the study I conducted was to determine whether post-auricular muscle activity reliably occurred in virtual auditory orienting tasks in humans. While this was plausible given that this is the function of the muscle in other species where it plays a non-vestigial role, it had yet to be determined at the time that I conducted research. The hypotheses were that the post-auricular muscle activity from each side would change as a function of the direction of the target speaker, and that the post-auricular muscle changes will be largest when the target speaker and the acoustic competition, or "noise," were spatially separated, thus being located on opposite sides of the head. These hypotheses were investigated by measuring the activity of the post-auricular muscle in twelve normal-hearing adults during a spatialized speech-in-noise listening task, also known as a Coordinate Response Measure (CRM).[18]

During a typical CRM task, participants listen to sentences that are of the form "Ready (CALL SIGN) go to (COLOUR) (NUMBER) now", and must correctly identify both the colour and number which correspond to the speaker who spoke the "call sign" which the participant was told to listen for. For example, if the participant was told to listen for the call sign "Charlie," they must first listen for which speakers voice says "Charlie," and then must continue to follow that voice long enough in order to hear which colour and number they instruct the participant to select. Selection of a colour and number is done by using a mouse to click the proper colour and number on a screen which is located in front of the participant in the sound booth. This screen is illustrated in Figure 5.

There are eight call signs, or names (Arrow, Baron, Charlie, Eagle, Hopper, Laker, Ringo, Tiger), four colours (red, green, white, and blue), and eight numbers (1–8). Every combination of call signs, colours, and numbers had the potential to be spoken by four male talkers and four female talkers. The CRM consists of high-quality recordings of eight talkers saying all 256 possible combinations of call signs and keywords,[19] thus yielding a total of 2,048 possible stimuli that could be heard by a participant. For our purposes, however, we limited the task to male talkers, and only used the call sign "Charlie". This reduced the possible number of possible stimuli to 128—with 32 possible permutations per male talker. The intelligibility of each of the keywords as spoken by each of the talkers has been examined, with results showing no significant advantage to the participant of being asked to identify any one of the potential keywords.[20]

Throughout this task, while the participant is listening for a specific “call-sign” within a sentence, there is also acoustic competition, or “noise” being played in order to make the task more challenging. In this case, the noise was in the form of competing sentences, whereby the only thing that differed between the target sentence and the acoustic competition was the call-signs, and the tone of the speaker’s voice. The orientations of the speaker and the noise were controlled experimentally in a virtual auditory space with insert earphones, while their post-auricular muscle reflex was measured via electrodes located around the pinnae (PAM, AAM, and SAM bilaterally). The amplitudes of the post-auricular response of each ear were compared between various conditions. The target speakers and acoustic competition had the potential to be co-localized or spatially separated at either –45˚(or 315˚azimuth) or +45˚azimuth, or co-localized at 0˚azimuth, yielding a total of five possible conditions. Thus, all conditions were limited to the frontal plane with respect to the participant.

The raw electrophysiological data was obtained using a Biosemi Active II biopotential system which provides unreferenced single-electrode responses. These were referenced offline and pre-processed using Matrix Laboratory (MATLAB; The Mathworks, Natick). The data was loaded separately for each participant. This allowed for the electrophysiological data to undergo standard pre-processing, which included referencing to ground and calculating differential measures, as well as for filtering to remove very high and low frequencies, thus eliminating any unwanted brain activity.

Following pre-processing, we first calculated the difference in voltage measured by the electrode activity over the post-auricular muscle and the electrode immediately in front of the ear at the pre-auricular point. This difference in voltage is called a differential measure. The electrode at the pre-auricular point was chosen as the reference point because there was less ear-related musculature in this location compared to that of the post-auricular muscle. Because we were more interested in the activity of the electrode that was directly over the post-auricular muscle, it was necessary to try to minimize other ear-related muscular responses in order to avoid conflicting measures with respect to the response sizes that we were obtaining from the PAM. This calculation was done for both the left and right sides, respectively. Figure 1 gives an example of data recorded from the left postauricular muscle during a single trial (approximately three seconds in length) which was referenced to the pre-auricular point on the left side over the duration of one second. Notice that there are many spikes that likely reflect muscle activation.

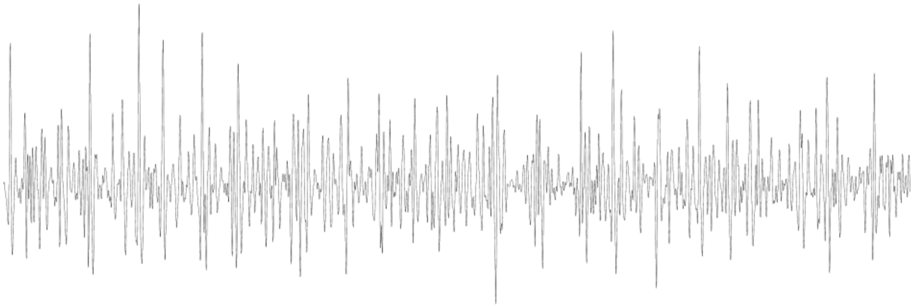

Fig. 1: Data extracted from MATLAB, illustrating activity recorded from the left postauricular muscle (referenced to the pre-auricular point on the left side) over the duration of one second. The protrusions shown in the above image are likely indicative of muscle activation.

We eliminated much lower frequency data because it is unlikely to have been muscle activity. There is quite a bit of cortical brain activity that occurs below 30 Hz, while electrical line noise occurs at 60 Hz. In particular, since there is a significant amount of low frequency associated with brain activity, and thus a failure to remove such frequencies could inundate the data and restrict the ability to confidently extract muscle-related activity. Conversely, we will see neural activity related to the peripheral auditory system (the auditory brainstem response) at frequencies between about 100 and 3000 Hz. The muscle-related (myogenic) activity that we were interested in occurs with a relatively fast wave, occurring over 4–5 milliseconds, thus resulting in a frequency of 200–250 Hz. Therefore, retaining a range of frequencies between 60 and 500 Hz was more than sufficient to attain our anticipated results whilst removing as much confounding activity as possible.

Next, the 300 milliseconds following each trigger was extracted. For this analysis, we recorded the PAM activity while participants engaged in the CRM task. This was done for the triggers at the start of each sentence, as well as for the triggers at the "call sign" since, in the conditions where the target speaker is opposite of the non-target speakers, the participant needs to accurately hear the target call sign in order to know which side to listen to.

However, this is not entirely true. Our initial hypothesis was that we would see muscle activity when a participant hears the call sign (i.e., Charlie), and we planned to compare that to the start of the sentence as our baseline. However, in furthering our analysis, it became apparent that when the target speaker and the acoustic competition are co-located, whether in the midline or on the left/right side, the participant will already know in what direction to listen. In the instances where the target speaker is opposite of the non-target speakers, participants will know what side the target is located on because there will be two voices on the side (the non-target speakers) and the target speaker would be alone on the other. Furthermore, because the level of the distractor voices is varied adaptively, participants may be able to determine the target speaker by the level difference at the outset of the sentence. For example, if the acoustic competition is softer than the target speaker, the participant does not need to wait to hear ‘Charlie’ to know which is the target voice. Therefore, we were able to deduce that the only true time in which participants need to wait for the target to say the call sign is when they are close to the threshold, and this is necessary only in the opposite condition. While we included time as a factor (the beginning of the sentence versus the beginning of the call sign), we did not anticipate there to be a significant difference in PAM activity when comparing the activity of the muscle response at sentence onset compared to that of when the call sign was said.

After preliminary modifications to the data are completed, there is typically a need to average multiple trials together to determine what is happening, allowing for a valid result to be obtained. While we have already accounted for interfering brain activity through the process of filtering very high and low frequencies from our initial dataset, the process of averaging can reduce random noise, whereas the response—which remains identical across trials—is not reduced. Therefore, the averaging process further improves the response to noise ratio. In this case, the specific muscle activations are unlikely to occur at the same time on every trial, so we are unable to simply average data across trials. However, since the muscle response should take about the same amount of time every time it happens, it should be similar in frequency across trials. For example, if it always takes between 4 and 5 milliseconds, there will be consistency in the frequency values, as they will fall between 200 and 250 Hz. Therefore, instead of averaging across trials, we averaged the frequencies across trials. If there is lots of muscle activity between 200 and 250 Hz, the average level in this frequency region should be higher.

To accomplish this method of analysis, a Fast Fourier Transform, also known as a frequency transform of the data was created with a 1 Hz resolution. These frequency transforms were then averaged across all trials of that type for each participant. The Fourier Transform is a mathematical formula that relates a signal from its original domain, in this case, time, to the same signal sampled in a frequency domain instead. Figure 2 is an example of an averaged frequency response.

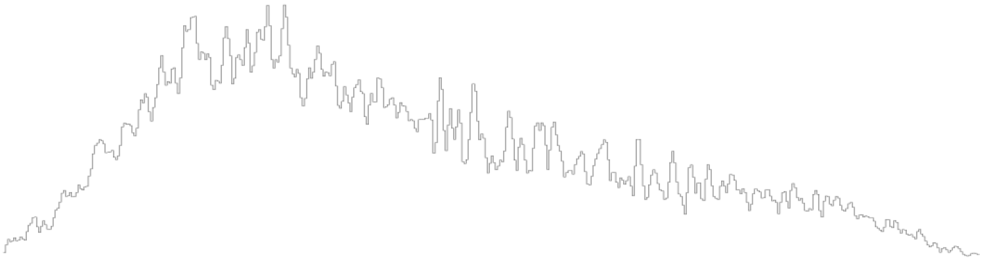

Fig. 2: An averaged frequency response between 30 and 500 Hz for a participant to the start of the sentence when played at the left speaker, from the left pre-auricular point. This transform was obtained through the use of the fft() function in MATLAB.

The level corresponding to the expected frequency range of the pre-auricular muscle (200-240 Hz) was calculated for each participant/electrode/condition by using data extracted from MATLAB. Since the size of the response may vary considerably across participants, each level was normalized to a Z score. This meant that each participant's mean response amplitude between 200 and 240 Hz (for each condition) had to be corrected by subtracting the participant's mean response amplitude in this frequency range, and then dividing by the participant's standard deviation (in the same frequency range). This converted all response amplitudes into Z scores, thus representing the number of standard deviations away from the participant's mean. The averaged Z scores for the left and right posterior muscles for all five conditions are shown in Figure 3. Data for both the start of the sentence and the start of the call sign is included in the figure.

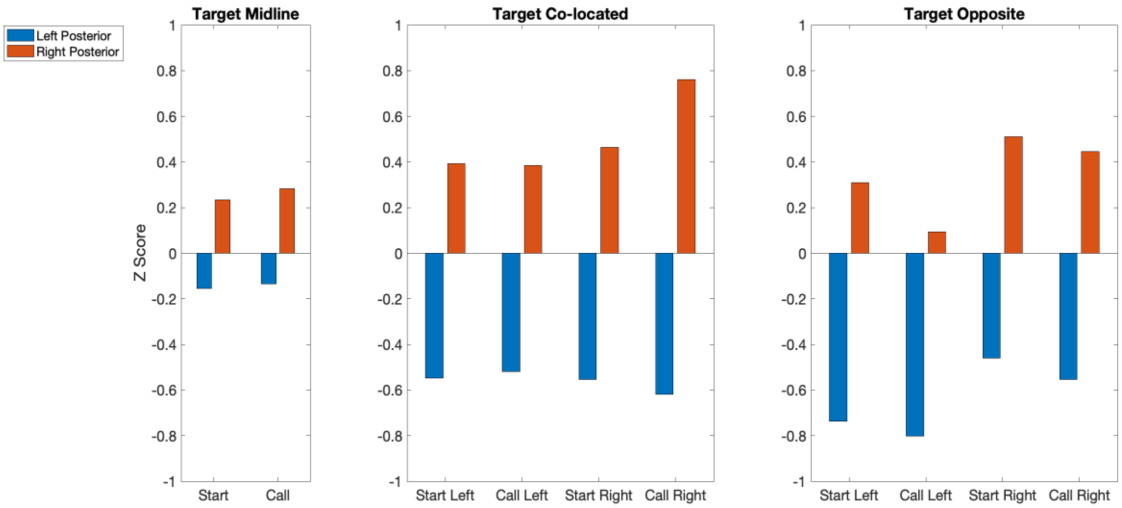

Fig. 3: Averaged Z scores for the left posterior muscles (blue bars) and the right posterior muscles (red bars) for the five conditions. Panel 1 and 2 illustrate a co-localization of the target speaker and the acoustic competition in the midline, to the left and the right, respectively. Panel 3 illustrates the target speaker being opposite of the acoustic competition—whereby the target speaker is first located on the left followed by on the right. This is shown at two separate times for each of the five conditions: the start of the sentence and when the call-sign is said—yielding a total of 10 Z scores for each muscle.

After obtaining our Z scores, a repeated measures Analysis of Variance (ANOVA) was calculated using Statistical Package for the Social Sciences (SPSS). The repeated factor is called a "within" subjects factor because comparisons are made multiple times ("repeated") "within" the same subject rather than across ("between") different subjects.[21] This was done by using these average Z scores from the left and right pre-auricular points as the dependent measure. This was done with three independent variables: Presentation Condition (illustrated in Table 2), Time (i.e., the start of the sentence versus the start of the call sign), and Ear of recording (left and right postauricular muscles, respectively). The average Z scores obtained from the left and right pre-auricular points were chosen as the dependent variable because it is what is continuously being measured across participants, regardless of the condition or time. In contrast, the independent variables consist of three “related groups”, thus indicating that the same subjects are present in all three groups. It is possible to have the same subjects in each group because each subject has been measured on three occasions on the same dependent variable.[21]

ANOVAs with repeated measures (within-subject factors) are particularly susceptible to the violation of the assumption of sphericity. Sphericity is the condition where the variances of the differences between all combinations of related groups are equal.[22] The violation of sphericity is serious for the repeated measures ANOVA, with violation causing the test to become too liberal (i.e., an increase in the Type I error rate; that is, the likelihood of detecting a statistically significant result when there isn’t one). Determining whether sphericity has been violated is very important; therefore, we tested our data for sphericity using a formal test called Mauchly's Test of Sphericity. In the cases where the assumption of sphericity was violated and the epsilon values of the Greenhouse-Geisser given in Mauchly’s test of sphericity were less than 0.75, we used the Greenhouse-Geisser correction.

There was no significant effect of time (i.e., the start of the sentence versus when the call-sign is said) or any interaction involving time, which is expected given how similar the pre-auricular muscle activity appears in Figure 3. The “Target Opposite” condition is the only condition in which one might need to wait for the prompt of the call sign in order to know which direction to listen to since the target speaker and the acoustic competition are co-located in all other conditions. Conversely, as previously mentioned, it is likely possible to know which side the target speaker is located on based on the level differences between the target speaker and the acoustic competition, except when the levels are similar as they would be when the participant is nearing their threshold. Therefore, we can conclude that there is no evidence for different post-auricular muscle activity at the call sign versus the start of the sentence. This is likely because it is easy to differentiate the location of the target speaker from that of the acoustic competition without hearing the call sign first.

There was a significant effect of ear (F(1) = 7.621, *p* = .019), which is to be expected given that the responses for the left ear and right ears differ from one another, which is illustrated in Figure 3. This result suggests that something is going on behind the ears, and it is in opposite directions on each side. More importantly, there was a significant interaction between ear and condition (F(2.327) = 2.006, *p* = .035), thus indicating that the activity behind the ears changed between the ears as a function of the direction of the target speaker. This is what we would expect since the way you activate your muscle at each ear should depend on where the target speaker is. Thus, while this suggests that our hypothesis was correct, it remains inconclusive at this time given that we would require follow-up tests showing the relationship between the side of stimulation and power of contraction, for example, in order to fully support such hypotheses.

1.2 Knowledge Gaps

The study involving the control of a computer game through PAMRs displayed results that indicated that six of the ten participants who took part in this task were successfully able to complete all three stages, thus indicating the ability of humans to selectively control the post-auricular muscle response during a non-auditory task.

Furthermore, the study involving control of a wheelchair reinforces this but also suggests that through training programs, humans can learn to elicit a response from their post-auricular muscles to complete a non-auditory task. However, despite the current research surrounding this muscular response during non-auditory tasks, only two studies have shown post-auricular muscle responses in listening tasks. Strauss et al. (2020) showed that the PAM was involved during a speech-in-noise task in soundfield conditions, and my research showed the same result, but with the stimuli being presented in a virtual auditory sound space. It is presently not known which mode of presentation (soundfield or virtual space) is most effective for eliciting the PAM in a speech in noise task, and impossible to directly compare the results of these studies given their methodological differences.

The present study sought to address this question directly by measuring post-auricular muscle activity using the same speech-in-noise method in both the soundfield and in a virtual space. It also expanded on previous research by recording activity from a wider set of relevant muscles, to ensure that post-auricular activation could be isolated from muscle activity at the other sites: the post-auricular muscles ipsilateral and contralateral to the stimulus, the anterior auricular muscle, the outer canthi of the ipsilateral eye, and the sternocleidomastoid muscle. Activity was measured in both adaptive-level paradigm (to find a speech-to-noise threshold) and in a fixed-level paradigm with a speech-in-noise threshold of +3 dB. Finally, the azimuths used in the present study (noise at 45˚ and speech at 135˚) were chosen on the basis of results of Strass et al., (2020) to encourage optimal engagement of the post-auricular muscle.

1.3 Study Introduction

1.3.1 Objectives and Hypotheses

The objective of this current project is to see whether the post-auricular muscle response is evoked in a speech-in-noise task both in soundfield and virtual conditions, and whether they varied between these conditions. In doing this, we looked to answer the following questions:

1. In what proportion of people can post-auricular muscle engagement (assessed electrophysiologically) be detected when engaged in a spatial speech-in-noise task, where the target is presented at 135° and the noise is presented at 45°, and:
    a. Both target and noise are presented from speakers in real space?
    b. Both target and noise are presented in a virtual sound space (delivered via earphones)?
2. How does the signal-to-noise ratio of the post-auricular myogenic response vary as a function of presentation mode (actual space versus virtual space) and azimuth for the following conditions?
    a. Target 135° and noise 45°
    b. Target 45° and noise 45°

To address these questions, our hypotheses were the following:

- Based on previous literature, post-auricular muscle activity should be reliably recorded in approximately two-thirds of all participants.

- Post-auricular muscle activity will be elicited in the same proportion of subjects when evoked via earphones in a virtual sound space as compared to when it is evoked from speakers in real space. Further, there will be no significant differences in the magnitude of post-auricular muscle activity between these conditions.
- Maximum muscle engagement will be observed in either condition when speech is presented at 135° and the noise is presented at 45°.

1.3.2 Methodology Overview

The current project investigated these hypotheses by measuring the activity of this muscle in nine normal-hearing adults during a spatialized speech-in-noise listening test. The orientations of the speaker and the noise were controlled experimentally in both soundfield and in a virtual auditory space with insert earphones, while the post-auricular muscle reflex was measured via electrodes located around the pinnae. The amplitudes of the post-auricular response of each ear were compared between eight conditions. These conditions are outlined in Table 2.

Chapter 2

Methods

2.1 Eligibility, Recruitment, and Study Population

This study was conducted in Dr. Steven Aiken's Electrophysiology Laboratory in the School of Communication Sciences and Disorders at Dalhousie University. All individuals who were above the age of 18 and who were of normal hearing were deemed eligible for participation within this study. The exclusion criteria for the study were limited to those with hearing loss. Since this was an exploratory study, the inclusion of individuals with hearing loss would require modifications that might impact results. The inclusion of these individuals would necessitate changes in stimulus levels to compensate for hearing loss, which might complicate the interpretation of results.

Participants were recruited through campus posters and word of mouth. All participants were provided a consent form before the initiation of the study, which had been pre-approved by the Dalhousie University's Research Ethics Board. We recruited a total of nine participants. All individuals were eligible for the study, and the nine participants completed the entire protocol. One participants (ID # 9) had their data omitted as a result of equipment malfunction, thus yielding a total of eight participants in the study (n=8). We had anticipated that one-third of these adults would not show a reliable, or any, post-auricular muscle response, based on previous research.[15,16] Therefore, we expected to have reliable responses in approximately 5-6 participants. As this was a pilot study, the effect sizes were unknown; however, as previously outlined, similar work has been successful with similar or fewer numbers of participants.[15,16] The eight enrolled participants ranged in age from 21 to 29 years. Table 1 lists the characteristics of participants in the study.

Table 1: Participant Characteristics (n=8)

Characteristics	N (8)
Age (years) Mean ± SD	24.5 ±0.928
Age Range (years)	21-29
Gender	
Female	4
Male	4

2.2 Procedure Description

2.2.1 Preliminary Hearing Screening

After consenting, participants noted whether or not they have had a hearing test within the last six months. If so, they did not need to undergo a hearing screening; however, if they had never had their hearing tested or if their last test was more than six months ago, the screening was necessary. Hearing screening was conducted in a sound-proof booth at a fixed level of 25 dB HL from 250 to 8000 Hertz (Hz) using EA-3A insert earphones.

2.2.2 Electrode Placement

Following any necessary initial screenings, participants had electrodes placed around their ears, eyes, and neck regions. 10mm diameter gold cup electrodes on a colour-coded ribbon cable were used. Skin was first cleaned using an alcohol swab, and was then prepped using Nuprep Skin Prep Gel in order to effectively improve conductivity and lower impedances. A conductive EEG paste was used to stick the electrodes directly to the skin for a secure connection. Impedance levels were checked before proceeding with any recordings. Impedances above 3kΩ were not accepted, and any areas reading an impedance level higher than this were further prepped with Nuprep. Impedance levels were monitored throughout to ensure that electrodes remained in place for accurate recordings.

It has been shown that the activity of the post-auricular muscle can be easily recorded by surface-level contacts on the mastoid (e.g., it is commonly recorded when the auditory brainstem responses (ABR) are obtained with a reference electrode on the mastoid), with surface potentials that are much larger than the neurogenic potentials often measured clinically.[23] Because of its isolated anatomical location on the scalp, selective electromyography (EMG) recording is achieved without significant artifact from adjacent muscles.[16] An electrode was placed overlying the mastoid region, which measured the right post-auricular muscle (PAM). Additional electrodes were placed over the region of the superior auricular muscle (SAM) and anterior auricular muscle (AAM). The electrode which acted as the ground electrode was placed on the SAM. A fourth electrode was placed on the back of the pinna of the right ear over the transverse auricular muscle (TAM).

Two additional electrodes were used to record eye and neck activity, respectively. An electrode was placed on the right outer canthus, or where the upper and lower eyelids meet, which monitored horizontal movements of the eye. Thus, any electrical activity that had been generated by eye movement could be identified at a later point as electrooculography (EOG) artifacts. Another electrode was placed over the sternocleidomastoid muscle—the most superficial and largest muscle in the front portion of the neck. In doing this, we were able to track any vestibular evoked myogenic potentials (VEMPs) which may have been elicited by this muscle during testing, in order to further isolate the PAM response. These six electrodes were localized to the right side of participants, as the listening task was oriented to their right ear, and thus, the activity elicited from this side was strongly of interest and would likely be much greater than that of any activity on the contralateral side. Two additional electrodes were placed on the contralateral side mimicking that of the PAM and TAM electrodes on the ipsilateral side, in the case that there was any measurable activity from these regions. It is likely that activity will be lateralized; however, this is said for our study population who have normal hearing. Such lateralization would likely dissipate for an individual with hearing impairment, as such individuals would have to rely on a contralateral response.

The placement of the ear and eye electrodes is outlined in Figure 4, with the ipsilateral (right) PAM, SAM, and AAM being labeled 1-3 respectively. The fourth electrode was placed on the TAM, which is not illustrated in the figure, as it is located behind the ear. Electrode 5 illustrates the location of the outer canthi (OCC), whereas electrode 6 illustrates the SCM electrode. Further, electrodes 7-8 mimic that of electrodes 1 and 4; however, as aforementioned, they are located on the contralateral (CON) side of the participant.

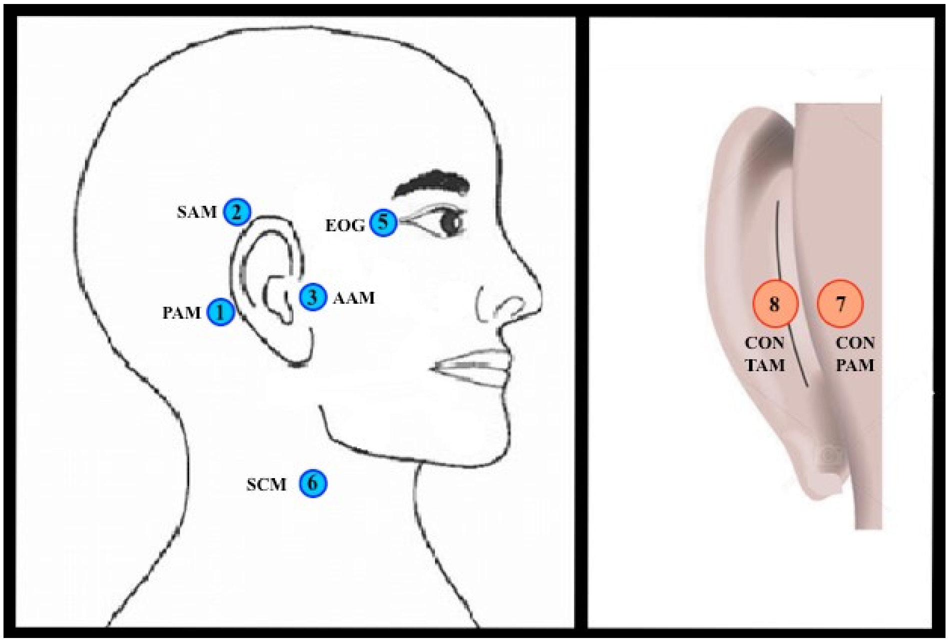

Fig. 4: (A) Placement of electrodes around the ears, eye, and neck. Each circle represents the location of an electrode, with the post-auricular muscle (PAM), the superior auricular muscle (SAM), and anterior auricular muscle of the right ear being labeled 1-3, respectively. The fourth electrode, which is not illustrated in (A), was placed behind the pinna on the right transverse auricular muscle (TAM). **(B)** Electrodes were placed on the right outer canthi (labeled 5) and the right sternocleidomastoid (SCM; labeled 6). **(C)** Electrodes 7 and 8 are shown on the left post-auricular and transverse auricular muscles, respectively, mimicking the placement of electrodes 1 and 4, only on the contralateral side with respect to the target speakers and acoustic competition.

To identify any post-auricular muscle activity that was recorded by the electrodes, we used a Smart EP optiAMP with custom acquisition software written in LabVIEW (National Instruments). The amplified signals were digitized by a National Instruments M-Series PXI 6259 in a real-time PXI system. Sounds were produced by a PXI 4461 dynamic signal acquisition card that was synchronized with the M-Series card via the PXI backplane. The real-time system was controlled (via shared network variables) by the experimenter and subject interface programs running in Microsoft Windows 10.

2.2.3 Coordinate Response Measure (CRM) Task

Following the placement of electrodes, participants were asked to engage in a speech-in-noise task, the CRM, which was conducted both in sound field through speakers in the sound booth, as well as through insert earphones to establish a virtual auditory space. During this task, speech-shaped noise was created by concatenating 96 sentences from all four male talkers (all colour and number combinations for three call signs), computing the fast-Fourier transform, randomizing the phases, and taking the inverse Fourier transform. The noise was randomly selected from this noise track on each trial (i.e., a portion matched in length to the stimulus).

While the call sign ("Charlie") and the sex of the speaker did not change, there were four different male voices used as the target speaker. These voices changed between presentations so that participants listened for the call sign as opposed to attuning to one specific target speaker's voice. Although there is no literature stating that one given speaker within the CRM task is easier to attune to, the ability to hear one given voice better could be subjective between participants. Thus, using four different voices allows for a generalizability of results. The interaction between the gender of the masker and the spatial separation has not been found to produce particularly large effects.[19] The participant had to select the color and number which corresponded to the directions given by the target speaker. Participants made their selections using a mouse from the monitor placed in front of them in the sound booth. An example of this monitor screen is illustrated in Figure 5. A response was only considered correct if the participant chose both the colour and number correctly on a given trial.

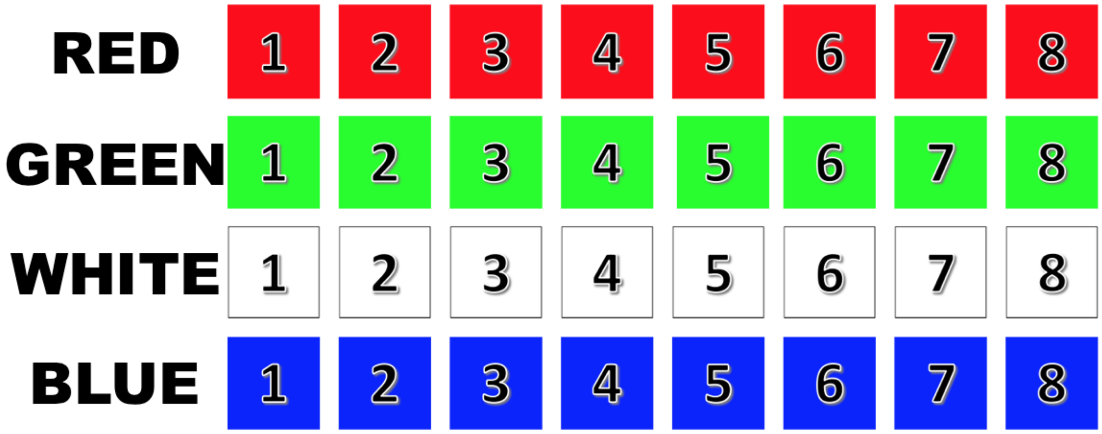

Fig. 5: CRM Task Monitor. Participants were prompted by a target speaker to select a specific color and number. In the instance that a participant is colourblind, the names of the colors were written beside their colors respectively.

2.2.4 Establishing a Signal-to-Noise Ratio

This task had four conditions, which were presented randomly to the participant. Each condition was split into two parts—an adaptive condition, and a fixed condition—yielding a total of eight possible conditions. To identify a target-to-competition threshold, the target sentence was played at a fixed level of 65 dB sound pressure level (SPL), which is the level of conversational speech from one meter away. This was done in order to identify the maximum level at which the competitive noise would reach before errors become consistent. The competing noise, on the other hand, was varied adaptively in level in order to establish a challenging signal-to-noise ratio (SNR) for the fixed conditions. SNR is a measure of the strength of the desired target speaker relative to that of the competing noise.

2.2.5 Adaptive and Fixed Conditions

For the adaptive conditions, there were three blocks of trials. The SNR began at 20 dB SPL (i.e., the noise was initially presented at 45 dB SPL). If a participant answered correctly, the noise increased in volume, whereas an incorrect answer caused the competitive noise to decrease in volume. An established threshold was dictated by a set number of oscillations, or reversals, due to a correct answer, which resulted in an increase in the volume of the competitive noise, followed by an incorrect answer, resulting in a decrease in the volume of the competitive noise. The volumes of the competitive noise were altered by +/–6 dB for the first two reversals and then switched to alternating by only +/–3 dB in order to accurately hone in on the SNR to be used for the fixed condition. There were a total of nine reversals in order to establish the SNR to be used for the fixed condition. The SNR was calculated as the arithmetic mean of the last six reversals, and was taken over the three trials to be used as the fixed SNR for the fixed condition.

During the fixed condition, there was one block of 20 presentations, all at a fixed SNR based on the average SNR obtained from the three adaptive trials. Conditions were randomized for participants, varying whether they began in sound field, or using headphones, as well as whether the target speaker and noise were co-localized or separated to begin. Each condition began with the adaptive component as it was required in order to establish an appropriate SNR for the fixed component within each condition.

2.2.6 Speaker and Noise Directionality within Conditions

Within these eight conditions, the target speaker and acoustic competition had the potential to be located together at 45˚, or separately at 45˚ and 135˚. In the case that the target speaker and acoustic competition were located separately, only the target speech would change locations, being presented behind the participant at 135˚. This was because the PAM was hypothesized to have the largest responses when the target noise was behind the individual. We held the level of elevation in a constant position of 0˚. This was accomplished through the use of a chinrest, which also ensured that ocular and VEMP activity were limited throughout the duration of the study. The possible combinations of conditions are illustrated in Table 2.

Table 2: Illustration showing four of the eight possible conditions that participants encountered. The first condition illustrates the target speaker (denoted “A” below) and the acoustic competition (i.e., the noise, denoted “B”) co-located at the front of the participant (45°), while the second condition demonstrates a separation in the target speaker and the acoustic competition, whereby the target speaker moves behind the participant (135°), while the noise remains in the front (45°). These first two conditions are done in soundfield (denoted “S”). Conversely, while the third and fourth conditions mimic that of the first and second conditions, these are completed in a virtual auditory space (denoted “V”).

Condition			**Location of Speaker**	
#	**Soundfield (S)** **Virtual (V)**	**Target Speaker (A)** **Noise (B)**	**45°**	**135°**
1	S	A	✔	
		B	✔	
2	S	A		✔
		B	✔	
3	V	A	✔	
		B	✔	
4	V	A		✔
		B	✔	

The virtual auditory spatialization was accomplished using head-related transfer functions for KEMAR large pinna from the CIPIC HRTF Database.[24] It was thought that the use of insert headphones would help to diminish the magnitude of responses that could be evoked due to the movement of the head or eyes by the participant when trying to orient to the sound. By using fixed speakers within the laboratory setting, if the target speaker was at 135˚ and the participant turned their head slightly or looked towards the stimulus, even slightly, a myogenic potential from the lateral ocular or sternocleidomastoid muscle might occur and be imitate activation of the post-auricular muscle. A chinrest was used to minimize this likelihood, making the two conditions as comparable to one another as possible. Figure 6A illustrates the direction of the sound source in sound field relative to the head, which is specified in terms of azimuth (horizontal plane), while Figure 6B illustrates that when these sound sources shift into a virtual auditory space, their orientation relative to the speaker remains the same between conditions.

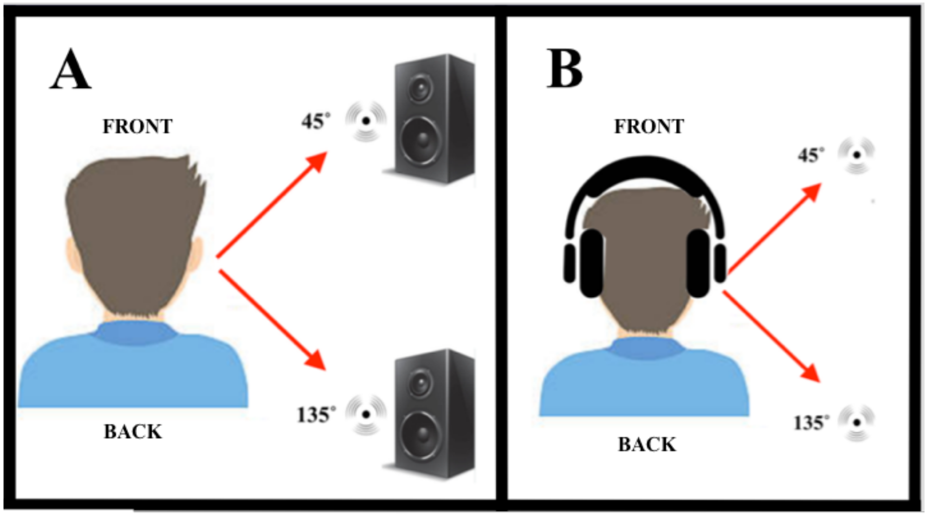

Fig. 6: (A) Demonstration of the possible directions that the target speakers and acoustic competition could be presented in terms of azimuth in soundfield (see Table 2 for a description of the possible conditions). **(B)** Illustration indicating that the target speakers and acoustic competition have the same presentation positions when conducted in a virtual auditory sound space under headphones. In both A and B, the target speaker varies between the anterior and posterior frontal plane. The competitive speech, however, is only presented from the anterior location (see Table 2 for a full description of the possible conditions). In both conditions, the elevation remains constant at 0˚. This is accomplished through the use of a chinrest, which also aided in limiting any possible ocular and VEMP activity.

2.3 Data Analysis Summary

2.3.1 Standard Pre-Processing of Data via MATLAB

Raw data files were first loaded into MATLAB. This data was parsed into epochs 86806 samples in length (at a 20k sample rate, i.e., 4.3403 seconds). Each epoch began concurrently with the stimulus and ended after 4.3403 seconds—the length of the longest stimulus. Thus, each epoch corresponded to one stimulus trial (i.e., the length of the auditory stimulus). While the number of epochs in the adaptive condition varied, the number of epochs remained constant at 20 within the fixed condition. The data were filtered between 10 and 1000Hz using a zero-phase 1000-point finite-impulse response filter (using MATLAB's filtfilt function). This was done for all channels. Epochs with levels in two channels exceeding 1.5x the interquartile level range were rejected as artefacts. This assumes that artefacts would likely affect more than one channel, and that large responses in a single channel might not be artefacts given their myogenic origin. The first 10 msec of each epoch was considered to be the baseline, and an average baseline for each condition was calculated as the mean root mean squared (RMS) level of the first 10 msec of each condition across all eight subjects. The level in each epoch (after the baseline) was averaged in a 10 msec moving boxcar window, advanced in 1-sample steps.

2.3.2 Detection of Post-Auricular Engagement via Peak-Picking Algorithm

Using the post-auricular channel for each epoch, a peak-picking algorithm was employed to detect engagement of the post-auricular muscle. First, the smoothed level track was low-pass filtered at 50 Hz (using 1000-point zero-phase finite-impulse response filter). This was normalized by divided by the baseline for each channel (to produce a signal/noise ratio). Any smaller peaks which were less than or equal to 0.5 SNR were zeroed out. The MATLAB findpeaks algorithm was applied to this signal. From this point, the 25 msec preceding and following each peak were extracted. Peaks too close to the beginning or ending of the epoch to include 25 msec preceding and following were excluded. The 50 msec surround each peak were then averaged in the time domain for each condition and participant. Time domain approach was used to facilitate so that the timing of muscle engagement could be compared across recording channels. Activity in the other channels was averaged at the same times to allow for comparison of activity across channels. The average SNR activity in all channels was then examined at these post-auricular muscle engagement times, to ensure that PAM activity was being recorded and not ocular or SCM activity. This is shown in Figure 8. Note that activity in other channels is often not showing a clear peak, suggesting the presence of background noise. To allow for comparisons of actual muscle activation, peak height was calculated by subtracting the mean level at the points 25 msec before and after the peak from the peak level. Peak heights were used for all subsequent statistical analyses.

2.3.3 Statistical Analyses

Statistical analyses were conducted in R 4.2.2 using the packages reshape2, dplyr, pastecs, and ez. Wilks test, using the pastecs package, showed no significant deviations from normality, skew, or kurtosis. A within-subjects' ANOVA was calculated using the ez package, with the factors speech azimuth (45˚ vs 135˚), presentation mode (spatial vs virtual), and channel (PAM, AAM, OCC, SCM, and CON). ANOVAs with repeated measures (within-subject factors) are particularly susceptible to the violation of the assumption of sphericity. In the cases where the assumption of sphericity was violated and the epsilon values of the Greenhouse-Geisser given in Mauchly’s test of sphericity were less than 0.75, we used the Greenhouse-Geisser correction. Student’s t-tests were used for post-hoc analyses, with Bonferroni corrections for family-wise error rate. This correction is an adjustment made to P-values when several dependent or independent statistical tests are being performed simultaneously on a single data set. This is done by dividing the critical P-value (α) by the number of comparisons being made.

Chapter 3

Results

In this study, we aimed to investigate the activity of the post-auricular muscle during a speech-in-noise listening task where the orientations of the speaker and the noise were controlled experimentally. This was done in order to determine how the signal-to-noise ratio of the post-auricular muscle varies as a function of presentation mode (actual sound space versus virtual auditory space) and azimuth (target speech and noise co-localized at 45° and target speech and noise spatially separated at 135° and 45°, respectively. The results of our study suggested that while the post-auricular response was reliably observed in all subjects, the magnitude of these responses was highly variable across participants with respect to presentation mode and azimuth. In this section, we will present a detailed analysis of our results and explore the factors that may have contributed to this variability.

3.1 Observation of Post-Auricular Muscle Responses

We hypothesized that post-auricular muscle activity would be recorded in approximately two-thirds of all participants, that such muscle activity would be elicited in the same proportion of subjects when evoked via earphones in virtual spaces when evoked from speakers in a real space, and that there would be no significant differences in the magnitude of post-auricular muscle responses between these presentation conditions. As a first step, we examined pre-processed single trial data for participants, comparing post-auricular activity to the activity of all other channels. In general, it was observed that post-auricular muscle activity was higher amplitude than activity in the other channels. An example of post-auricular amplitudes compared to other channels is illustrated in a Figure 7, showing a single-trial sweep for the first participant. In general, the peaks associated with PAM activity were not mirrored by peaks in the other channels; however, there were exceptions. For example, in the middle of the trial illustrated in Figure 7, we see peaks of ocular activity occurring at same time as PAM activity. There were also several peaks associated with the SCM which seemingly mirrored PAM activity. Note that although the peaks appeared to be larger in the SCM channel than the PAM channel on this trial, the baseline was also higher. This is largely why we focused on the SNR in order to better compare channels to one another.

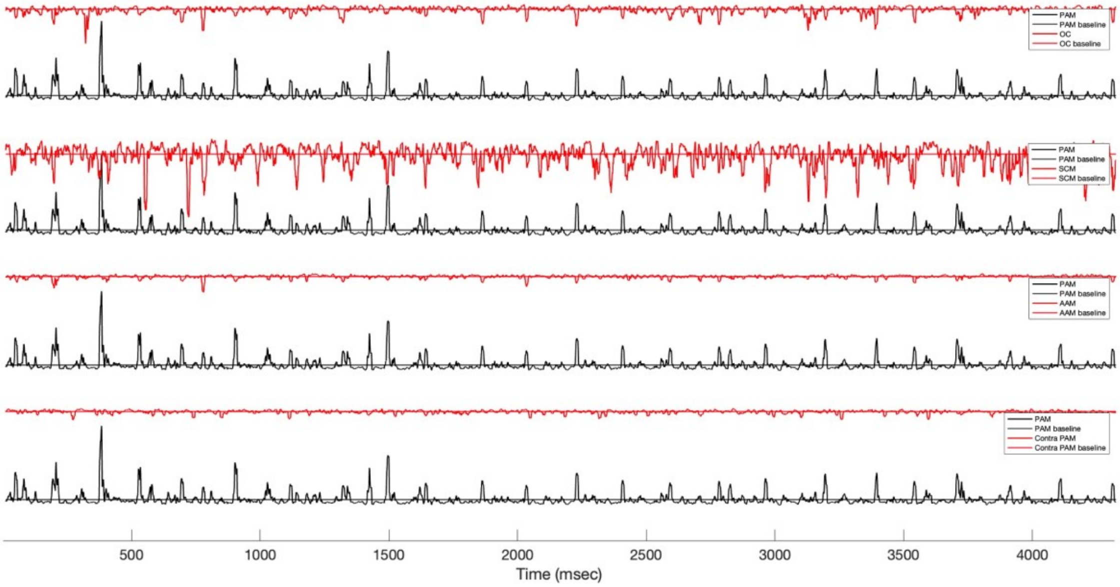

Fig. 7: Subject 1, Trial 1: Example showing PAM activity (lower; black) compared to the activity from the four other channels (OCC, SCM, AAM, and CON, respectively). The other channels are shown upside-down in red to facilitate comparison. The horizontal line crossing through illustrated the baseline for each channel. This single trial data is with reference to a single reading of the phrase “Ready Charlie go to [colour] [number] now”. All peaks are corresponding to the muscular activity observed in that respective channel.

In order to characterize the activity across all trials—to ensure that PAM activity was not simply secondary to activation of the SCM or ocular muscles—an averaging procedure was used with each average centering on a peak in PAM activity. To accomplish this, we used a peak-finding algorithm to detect all peaks (for each subject and condition) in the PAM channel and averaged activity in all channels at those times. Figure 8 illustrates this activity. Note that for some subjects and conditions, activity in other channels was high in level but without any peak that would indicate a myogenic potential (e.g., participant four in the spatial 45˚ condition). We thus calculated the peak height for each subject and condition by subtracting the edge values from the central peak value, whereby the edge values were arbitrarily selected to be times 25msec before and after each peak. This was done to ensure that the values were in fact muscle activation, and not simply higher levels of background noise associated with muscle tension. Peak heights were used for all further statistical analysis.

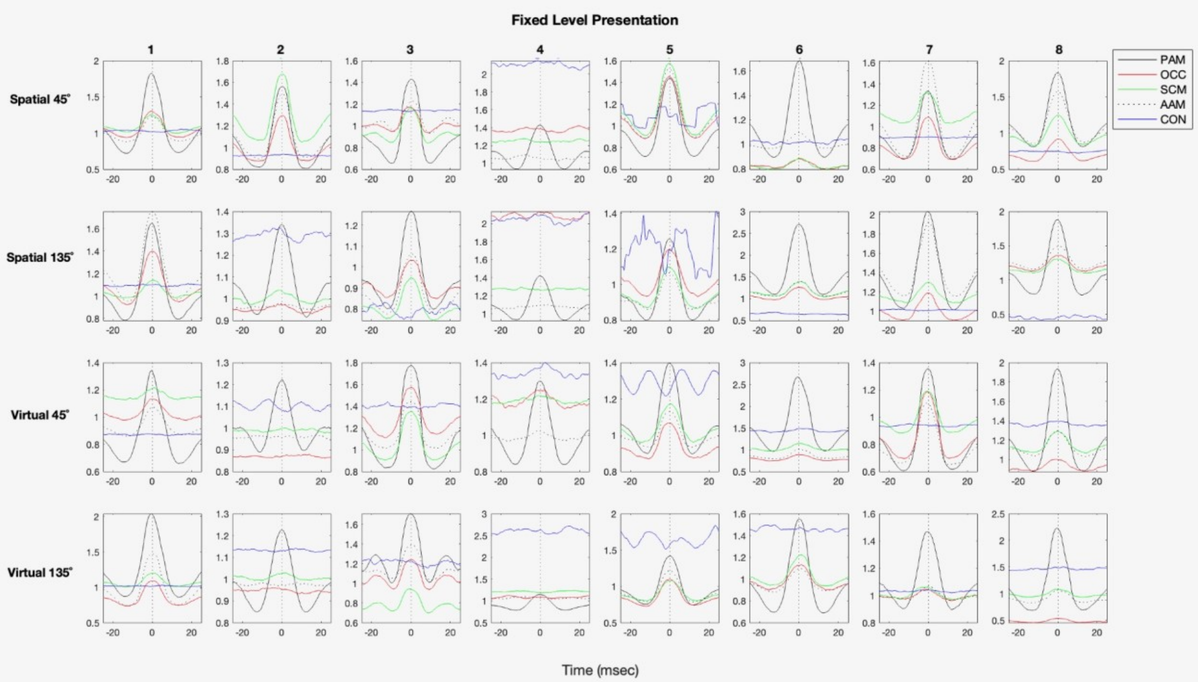

Fig. 8: Activity from OCC (red), SCM (green), AAM (grey-dashed), and CON (blue) channels time-locked to PAM activity. Both spatial and virtual conditions are illustrated for participants 1–8, with each condition being shown with speech presented at 45˚or 135˚.

Importantly, PAM activity was found in all subjects and in all conditions and was larger than activity in other channels in almost all subjects and conditions. In a few of the spatial conditions, some subjects showed AAM activity which was just as strong or stronger than PAM activity. This was true for subject 7 in the spatial condition when speech was presented at 45°. It is notable that there was less AAM activity observed in the virtual conditions as compared to that of the spatial conditions. Some subjects, notably subject 2 and subject 5, showed larger activity at neck in the spatial condition when speech was presented at 45°, suggesting that they were not engaging PAM primarily. Some subjects showed high levels of activity within a given channel which did not present as a peak, which could suggest general tension of that muscle, or noise within that channel. This was the case for the contralateral channel across all subjects and across all conditions.

3.2 Effect of Presentation Mode

We next looked at how the signal-to-noise ratio of the post-auricular myogenic response varied as a function of presentation mode (actual space versus virtual space) and azimuth with speech presented at 45° and at 135°, and noise remaining at 45°. This was investigated via a repeated measure ANOVA of peak height. There was a significant main effect of channel ($F_{(4,28)} = 27.07$, $p = 2.89e{-}09$), and a significant interaction between presentation mode and channel ($F_{(4,28)} = 3.17$, $p = 2.87e{-}02$). Paired t-tests showed that only AAM activity significantly varied between presentation modes and was significantly larger in the spatial presentation mode than in the virtual presentation mode ($t_{(15)} = 2.399$, $p = .02988$). There were no significant differences between presentation modes for any other muscle. These results are illustrated in Figure 9.

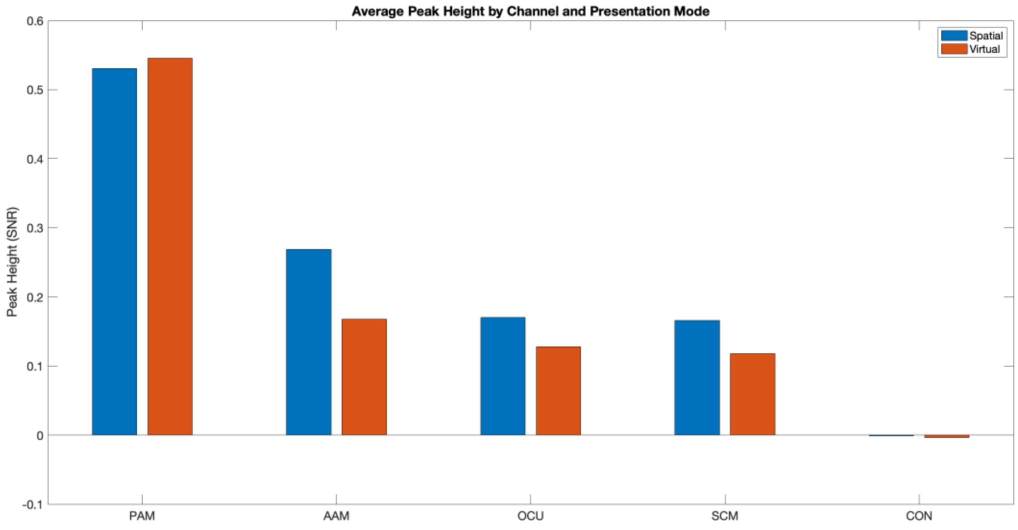

Fig. 9: Paired t-test results showing averaged peak heights (SNR) for spatial (blue bars) and virtual (red bars) presentation modes for each of the five channels. Results showed that the PAM response was significantly larger than all other channels. Further, results showed no significant difference between presentation modes for any other muscle aside from the AAM, suggesting that such responses are highly variable between individuals.

Paired t-tests also showed that activity at the PAM was greater than the AAM ($t_{(31)} = 7.197$, $p = 4.301e{-}08$). Activity at the AAM was greater than activity at the ocular or neck muscles ($t_{(31)} = 8.795$, $p = 6.261e{-}10$ and $t_{(31)} = 9.038$, $p = 3.386e{-}10$, respectively). Lastly, activity at the contralateral channel was significantly smaller than at all other channels.

3.3 Effect of Azimuth

There was no significant main effect of azimuth. To investigate how the PAM response varied as a function of azimuth, we first examined single-trial data for two different participants with speech presented at 45˚ versus 135˚. Figure 10 shows the PAM activity with speech presented at 45˚ (black) versus 135˚ (red) for Subject 1 (top) and Subject 7 (bottom). For Subject 7, we see larger amounts of PAM engagement when speech is presented at 135˚, which is what we had hypothesized. However, for Subject 1, similar PAM activity is seen when speech is at 45˚ versus at 135˚.

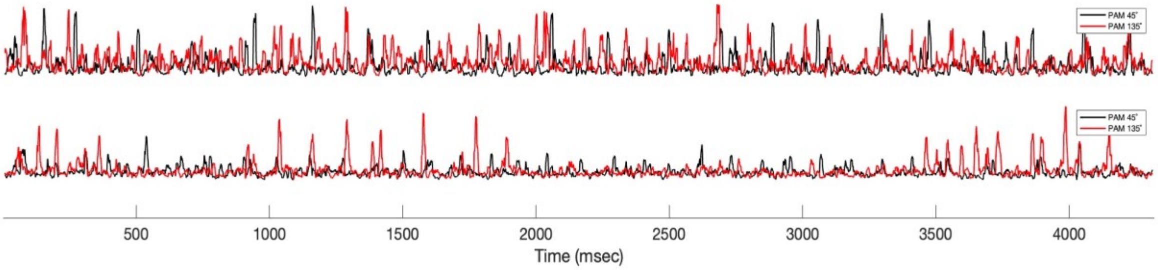

Fig. 10: Single trial data comparing activity when speech is presented at 45˚ (black) versus 135˚ (red) for Subject 1 (top) and Subject 7 (bottom).

We then examined average PAM activity for each participant in both the spatial and virtual conditions, with speech presented at 45˚and at 135˚. This is illustrated in Figure 11.

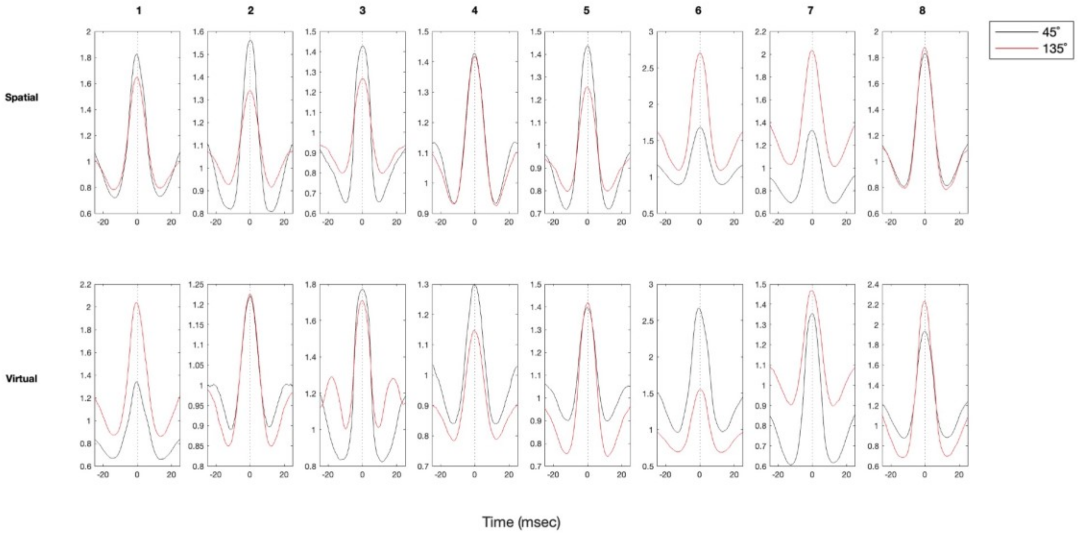

Fig. 11: Time-locked averaged PAM responses for spatial and virtual conditions illustrated for participants 1-8—with both conditions being shown when speech is presented at 45˚(black) or 135˚(red).

In some instances, the PAM response was larger at 135° for both the spatial and virtual conditions, which agreed with our hypothesis. For example, this was seen in Subject 7. However, there was an immense amount of variability with respect to this trend. For example, while Subject 1 had a larger PAM response with speech presented at 135° in the virtual condition, this was not the case for the spatial condition, as their PAM response was larger with speech presented at 45°. The reverse was true for Subject 6, who had a larger PAM response with speech presented at 135° in the spatial condition; however, they had a larger PAM response with speech presented at 45° in the virtual condition. This individual variability likely accounts for the lack of any significant effect of azimuth.

Chapter 4

Discussion

In this study, we measured PAM activity in all participants and we have demonstrated that PAM activity was significantly greater on the ipsilateral than the contralateral side. In most cases, this activity was much stronger than any simultaneous activity at the ocular or neck muscles, although large amounts of anterior auricular muscle activity were sometimes recorded. The fact that we were able to measure PAM activity across all participants was surprising, given that previous literature states that the response is only seen in roughly two-thirds of participants. This, however, could be due to the fact that the muscle responses were not quantified the same across all studies, and thus the criteria for what was considered to be a PAM response varied between studies. In saying this, it is probable that people are likely to engage the PAM to some degree in a speech in noise task, even if it's quite variable. Further, the positioning of the subject on the chin rest required them to lean forward, which is known to be conducive to recording a more robust response. This also could have attributed to an augmented PAM response across subjects. Lastly, subjects knew that the study was focused on the measurement of the PAM, and may have intentionally engaged the PAM to be helpful.

We determined that there were no significant differences in the level of PAM activation between spatial and virtual presentation modes. While PAM activation had previously been studied in soundfield and in virtual sound space independent of one another, this was the first time the two were compared against one another within the same data set. Because the location of the speech and noise were mimicked between both of these sound spaces, there is no reason why one person should hear better overall via speaker versus headphones. However, if there was to be a difference, you would expect the largest responses to be seen when the individual was listening to speech from behind them in either of these settings.

While PAM activation was reliably recorded across all participants, the pattern of these results was highly variable. Again, we expected that the PAM activation would be the highest when speech was presented at 135°; however, this was only true for two of the participants in the spatial condition, and three of the participants in the virtual condition. This variability should not be surprising, given that the PAM likely does not help with speech intelligibility in real life, since our ears are fixed to our head, and thus, the myogenic activity likely has minimal to no effect on intelligibility. If it were to have any significant effect on intelligibility, this would likely only be in a situation where the target was located behind the speaker, and the person could move their ears enough to significantly change the degree to which this source could be heard above any competing noise.

One note of interest is that of the three participants whose PAM activation was highest in the virtual condition with speech presented at 135˚, two of these three noted that they felt as though the task was similar to video games. This is interesting in that many video games (i.e., first-person shooter games) require players to be attune with their sound localization abilities, as you must listen for where your enemies are. Through the use of headphones, players can hear when an enemy player is to their side, or behind them. Thus, this could potentially have served in some participants as a means of unintentional PAM training, thus allowing them to produce a more robust and controlled PAM response when deliberately trying to hear behind them.

Additionally, in some cases, participants engaged the muscle for speech presented at 45° and co-located with the noise, sometimes doing so to a greater degree. This might show that subjects are naïve with respect to when engagement of the PAM is most likely to be helpful. This is unsurprising given that engagement probably does little to help.

4.1 Practical Implications

As previously mentioned, it has been shown that the activity of the PAM can be easily recorded by surface-level contacts on the mastoid (e.g., it is commonly recorded when the auditory brainstem responses (ABR) are obtained with a reference electrode on the mastoid), with surface potentials that are much larger than the neurogenic potentials often measured clinically[23], likely because of its isolated anatomical location on the scalp, which allows for selective electromyography (EMG) recording without artifacts from adjacent muscles.[16] In particular, the electrode which was placed mid-mastoid over the post-auricular muscle corresponds to the position which could be measured by a behind-the-ear hearing aid. Therefore, such a solution for recording the post-auricular muscle to aid in the control of directionality could potentially be implemented with surface contacts that do not require skin preparation, such as an electrode contact on a behind-the-ear hearing aid.

If participants do reliably activate their PAMs in spatialized speech-perception tasks, it could prove to be a major advancement in the field of natural science and engineering, as there would be the potential to restore this vestigial function through technology, providing human listeners with muscle-controlled directional hearing that may greatly improve listening in complex environments. Furthermore, if PAM activation is a learned function and can be enhanced through training sessions, creating an adaptive directional microphone in behind-the-ear hearing devices with surface contacts would prove to be beneficial for all potential users.

If this technology could be implemented into a hearing aid in order to enhance directional hearing in general, the focus of how to best make use of any PAMR's could quickly shift to hearing devices which are directionally focused in the front. Such devices that are directionally focused in the front could be a problem for someone in a wheelchair who is trying to have a conversation with their caretaker behind them, or simply for someone like a taxi driver who is trying to communicate with a client in the rear of the vehicle. By understanding the full range of directionality with respect to PAM activations, this could potentially lead to an understanding of how to detect when someone is trying to listen behind them. From here, hearing device manufacturers could design a mechanism that allows for a device that is directionally focused in the front to be turned off, allowing the user to voluntarily control their PAM to focus on sound-stimuli being presented from the rear.

4.2 Limitations

One limitation within this study was the small sample size. Whilst this sample size was comparable to that of other PAM related studies (both auditory and non-auditory), a large sample size would be beneficial for a more definitive result with respect to individual variability.

Second, while we accounted for ocular and neck responses, one way to allow us to be more confident in an auricular origin of our responses would be to have a large number of spatially distributed electrodes on the head, allowing for more in-depth analyses of source locations. Another option would be to use more invasive recording methods, such as electrodes that penetrate the skin.

Lastly, another limitation is that while we screened participants for any hearing loss, we could have gone deeper with this analysis by asking participants about any noise exposure or difficulty hearing in noise, which may in turn impact the results of this task and one's ability to orient the PAM. For example, if we were to inquire more heavily about noise exposure, while this may not appear within a baseline hearing screening, a measure such as an otoacoustic emissions (OAE) screening would serve as an extra layer of confirmation of cochlear status, as this will often detect damage from noise exposure sooner than standard audiometry would. Absent OAE would likely mean there is some dysfunction in the cochlea. Further, if we inquired about difficulty hearing in background noise, we could administer the QuickSIN—a speech-in-noise test that measures one's ability to hear in noise. Again, this is another parameter which we cannot reliably predict from the pure tone audiogram. Poor results on a QuickSIN (a large SNR loss) could impact an individual's performance on our speech-in-noise task.

4.3 Future Direction

With respect to future direction, the biggest question is whether or not training of this muscular response would allow for individuals to gain more control over their PAM responses. Studies have shown that training is effective in improving PAM activation during non-auditory tasks. As aforementioned, Schmalfuß L, Rupp R, Tuga MR, et al. investigated the ability of participants to steer a wheelchair using their PAMs.[16] Unlike our current study, this study examined the effects and the potential benefits of training the post-auricular muscles, whereby the primary goal of their training procedure was to increase the ability to activate both PAMs in order to use the auricular control system of a wheelchair. This was first accomplished through the completion of a series of computer games that focused on the training of lateralized PAM activations, followed by more complex games that trained higher functions such as driving skills. These driving skills mimicked the control of a wheelchair within a virtual setting. This virtual wheelchair navigation mode was the same as in powered wheelchair driving.[16]

Since other studies have shown that training is effective in improving PAM activation during a non-auditory task, it is likely that participants would be able to improve their PAM activation during an auditory task as well if they were to undergo a series of training sessions. Since our results suggest that PAM activation is already reliably occurring across all participants, it would be worth studying how such responses can be enhanced as a learned function in future studies. One way that this could be accomplished would be to implement a reward system such that if participants successfully engage the muscle and display their ability to listen in a particular direction, we would reward them by making the task easier. Conversely, the difficulty of the task would increase if an individual failed to display this activation.

Chapter 5

Conclusions

This study suggests that there is evidence for reliable post-auricular muscle activation across all participants, as it was shown that all participants engaged the PAM in a speech-in-noise task. This activity sometimes co-occurred with activity of the AAM and to a lesser degree, the neck and ocular muscles. Further, it was found that this activity was highly variable across subjects, with some subjects engaging the muscle more for speech presented at 45˚ and some engaging the muscle for speech presented at 135˚. Importantly, there was no significant difference in the amount of muscle engagement between conditions in which sound was presented in the sound field and in which sound was presented in a virtual sound space. The engagement in virtual sound space suggest that PAM activation occurs as a consequence of spatially directed attention, even when changes in pinna orientation are unlikely to have any effect on the sound that is heard.

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