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Effect of a Small Change in Auricle Projection on Sound Localization

Elizabeth N. Surface

A dissertation submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

Partial Fulfillment of the Requirements

For degree of

Doctor of Audiology

Department of Communication Sciences and Disorders

May 2021

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ABSTRACT

Pinnae assist in sound localization, and changes in auricle shape, position, or projection can theoretically alter the perceived position of a sound. The minimal displacement required to affect perceived sound location is undefined. This study quantified the error in horizontal sound localization when auricle projection is slightly decreased. The study was conducted at two sites by different experimenters, using different (though similar) systems, over a year apart. There were 21 normal-hearing participants: 11 at the University of Virginia (UVA) and 10 at James Madison University (JMU). Both UVA and JMU protocols involved a normal listening condition and a second condition with a headband that slightly altered pinnae projection by pushing the helixes medially against the temporal bones. Participants identified the location of a short, moderate-intensity noise burst from one of 8 speakers distributed in a horizontal array. Root mean squared error was calculated from tests of 48 trials. Localization errors in the UVA data were greater with the headband than without ($t_{10}=2.6$; $p=.023$; Cohen's $d=.8$ or 'large' effect size). The experiment was repeated at JMU and results replicated; localization errors were greater with than without the headband ($t_9=2.4$; $p=.034$; Cohen's $d=.8$). There was no effect of testing order and no consistent direction of error in either protocol. None of six anatomical measurements of pinnae correlated with the decrease in azimuth accuracy. Combined data from both experiments show a highly significant effect of the slightly medialized helix ($t_{20}=3.6$, $p=.002$; $d=.9$). These data indicate the minimum pinna change required to alter sound localization is at least as small as the 15 mm average movement of the helix or 29 degree reduction in auricle projection. These data on psychoacoustic effect of altering auricle projection may be of relevance after otoplastic operations.

Chapter I

INTRODUCTION

It is well known that the interaural time delay and interaural intensity difference contribute to horizontal sound localization. The auricular shape is thought to contribute to sound localization in all dimensions, but the magnitude of its contribution, specifically to horizontal sound localization, is less defined (Nelson, Reeder, Holden, & Firszt, 2018; Risoud et al., 2018).

The unique shapes and grooves of the outer ear (along with upper body shape) filter incoming sounds and characterize how the ear receives sounds from a particular point in space. This response is known as a head-related transfer function (HRTF). A person's two unique HRTFs (one from each ear) enhance the ability to locate sound (Blauert, 1982). A change in the shape, position, or projection of the pinna would alter the HRTF, leading to unfamiliar spectral cues from external sounds and, theoretically, a change in perceived sound locations (Gardner, 1973).

Many studies focus on the importance of pinna cues for localizing in the vertical plane, however it is also useful for sound localization in the horizontal plane. Pinna cues do not contribute to horizontal sound localization to the degree that interaural time delays (ITD) and interaural level differences (ILD) do, but they are useful in resolving ambiguities when ITDs and ILDs are not sufficient in identifying sound sources. For example, pinna cues are important for identifying sounds originating in the cone of confusion, a hypothetical cone-shaped area radiating outwards from a listener's ear. In this area in space, sounds have similar ITDs and ILDs, causing confusion for the listener

when attempting to locate the sound. Pinna cues are also essential for listeners with asymmetric hearing thresholds, who cannot rely on binaural cues.

Gardner and Gardner (1973) demonstrated long ago that wideband sounds originating from various elevations were increasingly difficult to localize with progressive pinnae coverage. More recent studies using ear molds in the auricle show immediate changes in sound localization, with slow adaptation to such changes over several days (Carlile, Balachandar, & Kelly, 2014; Hofman, Van Riswick, & Van Opstal, 1998; Trapeau, Aubrais, & Schonwiesner, 2016). There is no generally accepted time-course of adaptation, but a small change in the HRTF would be expected to cause a small decrease in localization accuracy that could return to normal after some practice with the altered pinna cues. Previous studies involved relatively major changes to the pinna (such as filling 40% of the conchal bowl), so it is not known how small a change is necessary for any decrease in localization accuracy.

The effect of a minimal auricle alteration becomes relevant in the profession of otology, where changes to pinnae are common and the effect on sound localization is relatively unexplored. Subtle alterations in the size and shape of the lips, nose, eyelids, and ears can create readily noticeable changes to a person's face. Facial plastic and reconstructive surgeons learn to balance desired changes in shape with functional implications. This balance is especially true and well-studied in the practice of rhinoplasty. However, functional implications of surgery on the auricle, be it otoplasty, microtia repair, or reconstruction after skin-cancer excision, are rarely discussed. While it is possible that auricular surgery does not alter hearing function to a clinically

significant degree, it is also possible that a large percentage of the major shape-changing surgeries are performed early in childhood when any subtle functional change would not be vocalized by the patient. To use a metaphor of a different facial feature, consider if reductive rhinoplasty were performed on 5-year-olds. The reduction of the size of nose overall or particular areas of the nose to obtain a more desirable appearance can lead to nasal airway restrictions both immediately after surgery or long term. If a five year old had reductive rhinoplasty surgery, they would likely not perceive their breathing was restricted. This leads one to wonder about a similar effect in otoplasty.

Projection of the auricle is defined as the angle at which the helix sits (projects) away from skull. Normal auricular projection is approximately 15 mm or 29 degrees, but patients can have wide variability in auricular projection. The goal of otoplasty surgery (“pinning the ears back”) is to reduce the projection of prominent auricles by moving the helix closer to the skull. Could otoplasty surgery have an effect on functional hearing? Specifically, this study aims to investigate whether changes in auricle position may alter horizontal localization abilities. We examined the effect of a small change in the projection of the auricle, by gently pushing the helix medially to the temporal bone with a thin headband, on horizontal sound localization accuracy.

Chapter II

LITERATURE REVIEW

Sound localization, the ability to determine the source of a sound in space, is a complex process involving the peripheral and central auditory systems. Different mechanisms of the auditory system are used to identify the location of sound in different planes.

Horizontal localization relies heavily on binaural cues such as interaural time delays (ITD) and interaural level differences (ILD). Localizing in the vertical and front-back planes is enhanced by monaural spatial cues created by one's torso and outer ear. Proper sound localization is important for environmental awareness and detecting possible threats. The ability to localize a sound source can alert humans to impending danger (e.g. an approaching car) so that they may act to remove themselves from vulnerability. It is also important in daily life situations, such as finding one's phone when it's ringing, knowing the direction from which one's name was called, and many other simple daily instances that normal hearing individuals with proper localization abilities likely take for granted.

Sound localization is an important benefit of binaural hearing. ITDs and ILDs are both heavily used in identifying sound in the horizontal plane, but each cue is more or less helpful depending on the incoming sound. ITDs are more important for identifying locations of low frequency sounds, while ILDs are relied on for high frequency sound localization, as outlined by the duplex theory of sound (Woodworth, 1938; Macpherson & Middlebrooks, 2002). ILDs are the dominant binaural cue for localizing sounds above ~1700 Hz based on the size of the adult human head (Kumpik & King, 2019). These cues are most helpful with symmetric bilateral hearing thresholds.

Monaural spectral cues (largely dependent on the filtering and funneling of sound by the pinna) are also important for sound localization. While binaural cues are primarily used for accurate localization in the horizontal plane, spectral cues are effective for front-back and vertical localization. As sound waves reflect off of an individual's torso and various features of the outer ear, they are filtered and funneled into the external auditory canal, providing important spectral cues for determining the location of the sound source in space. Sound sources in different locations will be frequency-shaped uniquely based on the angle of arrival to the ear. Because of the small size of the pinna and its grooves, high frequency (short wavelength) sounds are more likely to be localized than low frequency sounds (Musicant & Butler, 1984; Butler & Humanski, 1992). Spatial cues can assist clearing up cones of confusion, and provide information when differentiating front-back localization in the horizontal plane (Kumpik & King, 2019).

It has been shown that monaural cues alone provide little help in lateral localization for normal-hearing listeners (Macpherson & Middlebrooks, 2002); however, studies have found that most listeners with unilateral severe-profound hearing loss were still able to accurately localize broadband and high pass noise stimuli in the horizontal plane (Slattery & Middlebrooks, 1994; Rothpletz, Wightman, Kistler, 2012). In fact, Slattery and Middlebrooks (1994) compared subjects with unilateral hearing loss and normal listeners with a plug in one ear to simulate an asymmetrical hearing loss for a localization task in the horizontal plane. They found that the control (normal-hearing listeners with the plug) made localization errors more when stimuli came from speakers on the side of the unplugged ear, which is expected. Two of the unilateral listeners performed similarly to the controls, while the other three localized with the same

accuracy on each side. This could suggest these listeners have adapted to the hearing loss and rely on spectral cues from their better ear to help localize in the horizontal plane.

The contribution of spectral cues in the lateral plane for listeners with single-sided deafness was supported by Agterberg and others (2014) when they explored the contribution of spectral cues to lateral localization for individuals with single sided deafness (SSD). They used 3 different stimuli: broadband (0.5-20kHz), high-pass filtered (>3kHz) and low-pass filtered (<1.5kHz) noise. They varied the level with each presentation to prevent subjects from relying on stimulus level for localization. As mentioned earlier, pinna cues are most beneficial for high frequency sounds, thus they found that some SSD listeners were able to accurately localize high-pass filtered and broadband noise. When experimenters filled the cavities of the pinna of those subjects' good ears, diminishing spectral cues, their performance drastically deteriorated. There was great inter-subject variability, which experimenters later attributed to varying degree of high frequency hearing loss.

Filling or partially filling the concha with a mold has been shown to initially affect localization in the vertical plane (Hofman, Van Riswick & Van Opstal, 1998; Van Wanrooij & Van Opstal, 2005; Carlile, Balachandar & Kelly, 2014). Hoffman and others (1998) found that participants with bilateral molds began to regain localization abilities in elevation after four weeks. A study by Van Wanrooij and Van Opstal in 2005 further explored the plasticity of sound localization by asking subjects to wear an ear mold in only one ear at a time. This allowed for drastically different spectral cues in the ear with the mold, while also creating a radical imbalance of spectral cues between ears. Localization abilities of all participants were immediately affected after insertion of the

molds. Seven participants plateaued on their performance after 7 days, however they did not reach optimal localization performance due to inaccuracy on the ipsilateral elevation task. Three of those participants volunteered to wear the mold for as long as 22 days, but no improvements were made with time. Five participants had varying improvements over time and never plateaued. Although localization performance with molds was not as accurate as localization without molds, adaptation to the new spectral cues was seen with both binaural and monaural molds. Additionally, aftereffects were not seen for binaural or monaural molds; performance immediately after removal of molds was not different from performance before molds were inserted (Hofman et al., 1998; Van Wanrooij & Van Opstal, 2005). Lack of aftereffects was found in another mold study in which localization accuracy was regained after several weeks of wearing molds (Trapeau, Aubrais, Schonwiesner, 2016). These participants reinserted the molds after a week without wearing them and completed the localization tasks again, resulting in the same localization abilities as the last day of testing with ear molds (end of week 2). These studies demonstrate that it is possible for most individuals to sufficiently adapt to new spectral cues in a relatively short period of time, and they may even be able to associate multiple spectral profiles to one sound source location.

The contribution of spectral cues for localizing is evident. Drastically altering the pinna will diminish localization abilities in elevation, which may be partially restored with practice in everyday life. Practically, this information is useful for SSD listeners who rely on spectral cues more heavily without access to binaural cues. This is also relevant information for individuals who may have severely altered pinnae due to an accident or trauma. However, these studies provide little information regarding the effect

of a slight pinna alteration, such as that seen in otoplasty (i.e. pinning of ears) for individuals with prominent or protruding ears.

Almost 23,000 elective otoplastic operations were performed in the US in 2018 (2018 Plastic Surgery Statistics Report, 2019). Otoplasty is a common plastic surgery performed on children to reduce the projection of the auricle. According to a study of 67 children with prominent ears by Songu and Kutlu (2014a), the health-related quality of life was raised in 94% of children post-operation, and negative Glasgow children's benefit inventory scores were not found in any case. The same researchers evaluated the psychosocial profile of 198 children who underwent otoplasty procedures and found significantly lowered scores on the Child Behavioral Checklist in areas such as anxiety, depression, difficulties in thinking and total behavioral problems (Songu and Kutlu, 2014b). The appropriate corrective surgery for prominent ears can thus leave a positive impact on one's life. Although generally considered a low-risk surgery, there are possible late complications of otoplasty that have the potential to cause more psychological harm than good. Early complications (haematoma, bleeding, infection, skin necrosis and wound dehiscence) are uncommon, occurring in 0-8.4% of cases (Limandjaja, Breugam, Mink van der Molen & Kon, 2009). Reports of late complications however, vary from 0 to 47% due to differences in follow-up length and surgical technique. Some of these late complications are scarring, suture extrusion, hypersensitivity, asymmetry, and recurrence (Limandjaja et al., 2009).

The risks commonly mentioned revolve around the surgical and healing complications and possible dissatisfaction with cosmetic results. Functional implications for hearing are not commonly discussed prior to surgery or reported postoperatively. To

our knowledge, the only other study to consider functional implications of reducing pinna projection was McNeill and others (2013). They found that repositioning the pinna to mimic the change seen in otoplasty affected speech reception and intelligibility scores. Such a finding calls for more research and could possibly impact the informed consent process.

In summary, while it is well known that the interaural time delays and interaural intensity differences predominately contribute to horizontal sound localization, the magnitude of the auricle's contribution, is less defined (Nelson, Reeder, Holden, & Firszt, 2018; Risoud et al., 2018). The effect of a large disturbance to the ear, such as filling the concha or obstructing the ear canal with a foam plug, has been demonstrated, but the functional implications of slighter pinnae disturbances have room to be explored. As it is known that localizing in the vertical plane is heavily dependent on the auricle for spectral cues, it would not be a surprise if altering the pinnae disrupted localization accuracy in this plane. A less likely result of altering auricles would be a significant decrease in the ability to localize in the horizontal plane. The present study examined the effects of a subtle reduction in pinna projection, similar to what occurs in an otoplasty, on sound localization accuracy in the horizontal plane.

Chapter III

METHODS

Data collection took place at two separate sites with different experimenters and participants over a year apart. The conditions and procedures varied slightly between each test site and thus will be explained below separately.

The protocol was approved by IRB 12490 at the University of Virginia. Testing at the University of Virginia took place in the Otolaryngology clinic in an empty procedure room in 2015. The experimental setup (described below) was placed against back and sidewalls. There were 11 participants, all of which were employees or graduate students working in the clinic, both male and female. All participants reported hearing thresholds within normal limits. The experimenters define normal hearing as hearing thresholds less than 25 dB HL across all audiometric test frequencies. Participants' hearing thresholds were not measured prior to testing as a part of this study because they regularly undergo audiometric tests in the clinic in which they work.

The experiment was replicated at James Madison University in 2017. The protocol was approved by IRB 16-0301 at James Madison University. Testing took place in a quiet auditory research laboratory (5 x 6 m) in an isolated suite of an academic building. Testing was not conducted in a sound proof booth. The experimental setup was in the middle of the room, at least 2 m from any wall. There were 10 participants: 2 males, 8 females. All participants were normal hearing young adults, none of which had previously participated in this study. Again, audiometric thresholds were not obtained as a part of this study; however, participants regularly had their hearing tested during labs to

fulfill requirements of their psychoacoustics class in which they were currently enrolled. All participants provided informed consent.

Experimental Setup and Stimuli

An 8-speaker array was placed on a table with a laptop in the center, as shown in Figure 1. The speakers were in a 180° semi-circle (0.6 to 0.7 m from the listeners) with four speakers on each side of the laptop, 20 degrees apart. The speaker angles and setup remained constant throughout testing. Similar, but separate setups were used for each test location.



Figure 1. 8-Speaker Array. This speaker system was validated by Ganev (2017).

A test consisted of 48 trials, 6 blocks of 8 noise bursts, where each speaker was activated once per block in random order. Each noise was a different random sample of Gaussian noise, 250 ms in duration with instantaneous rise/decay times, and a random intensity rove of 2 dB. Noises averaged 55 dBA across the 8 speakers with ± 1.3 dB

difference (3.3 dB including the rove). Speaker 1 is the speaker to the immediate left of the participant, and the speakers are numbered consecutively 1-8 in the array to speaker 8, immediately to the right of the subject. Participants clicked a button on the computer, #1-8, to indicate the perceived location of the sound. Participants were instructed to refrain from moving their head during testing.

Test Conditions

In the UVA protocol, there were four test conditions (Figure 2). The normal condition was performed twice, thus each participant performed a total of five tests. Each subject made 48 judgments for each test condition. The normal condition was tested first, followed by two additional tests with one ear and then the opposite ear plugged with a foam in-the-canal earplug designed to provide approximately 30 dB of attenuation. The two tests with one ear plugged at a time were conducted to later allow for the comparison of magnitude of localization errors between a unilateral conductive hearing loss and the decrease in auricle projection induced by the headband. The fourth test condition used the headband to gently pin both right and left auricles to the temporal bones reducing auricle projection by an average of 15 mm or approximately 29 degrees. A repeated 'normal' test was conducted as the fifth and final test protocol.

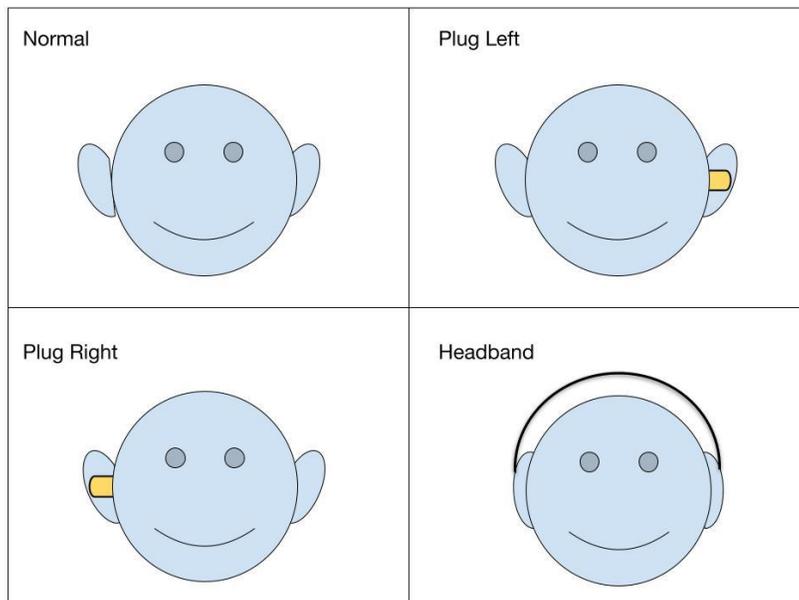


Figure 2. Test Conditions at UVA.

In the JMU protocol, each participant was only tested twice; the normal and headband conditions were each tested once and in random order. The two tests with plugged ears were not performed in the JMU protocol. Table 1 indicates the order of UVA and JMU test conditions.

Table 1. Order of test conditions. JMU tests were completed in random order.

UVA Protocol	Test Order	JMU Protocol	Test Order
Normal	Test 1	Normal	Random Order
Left ear plugged	Test 2	Headband	
Right ear plugged	Test 3		
Headband	Test 4		
Normal	Test 5		

Pictures were taken of the ears of consenting participants in the UVA protocol. Five measurements were then recorded from side and back images of right ears. The height and width were measured from the side. Distance from lateral edge of pinna to the temporal bone at the top, middle, and bottom of the auricle were measured from the back

(seen as A, B, and C respectively in Figure 3). These five measurements were later used in 10 correlations between these pinna characteristics and normal localization accuracy and change in accuracy with displaced auricles.

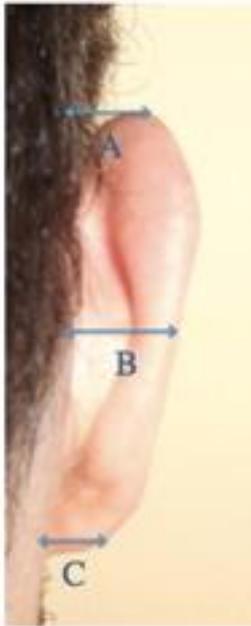


Figure 3. Ear Measurements from Back.

Data Analysis

Sound presentation and data collection were programmed in Matlab 2016b; results were analyzed in SPSS (V24). Percent of correct judgments and degrees of error were the primary dependent variables in this study. Localization error was measured by the root mean squared of the error in degrees. That is, if the noise was presented from speaker 8, and the subject perceived the noise to come from speaker 7, there would be 20 degrees of error in localizing the sound in that trial. Errors could happen in either direction; if random responses from all 48 trials were averaged, errors made in the positive and negative direction would average to zero indicating no consistent direction of error despite low accuracy. Using the root mean square (RMS) of the localization errors allows

the magnitude of error for all 48 judgments to be averaged without cancelling because of the direction of error.

Repeated-measures ANOVA was used to compare testing conditions; an independent samples t-test compared results from JMU and UVA protocols; one-sample t-tests analyzed mean errors; Pearson product-moment correlations quantified anatomical covariates. The mean angle of auricle projection (29 degrees) was calculated based on ear measurements obtained from the UVA participants. For calibration purposes only, the duration was increased to 6 s and a stable dBA fast level was recorded using an NTi Acoustics XL2 sound level meter with Class 1 ½ inch calibrated microphone on a long cable clamped on a ring stand at the approximate nasion position (with no one seated in front of the computer).

Chapter IV

RESULTS

Localization error (in RMS) was greater with the headband than without in the UVA data (using a paired-samples test, $t_{10} = 2.6$, $p = .023$, effect size Cohen's $d = .8$ or 'large'). The large effect was unexpected, so the experiment was repeated in a different location (JMU), over a year later, and with a different experimenter and participants. In the JMU data, localization errors were greater with than without the headband, ($t_9 = 2.4$, $p = .034$, Cohen's $d = .8$) replicating results from the UVA data. The localization error from both the UVA and JMU experiments were combined and remained significant ($t_{20} = 3.6$, $p = .002$; $d = .9$; Figure 4).

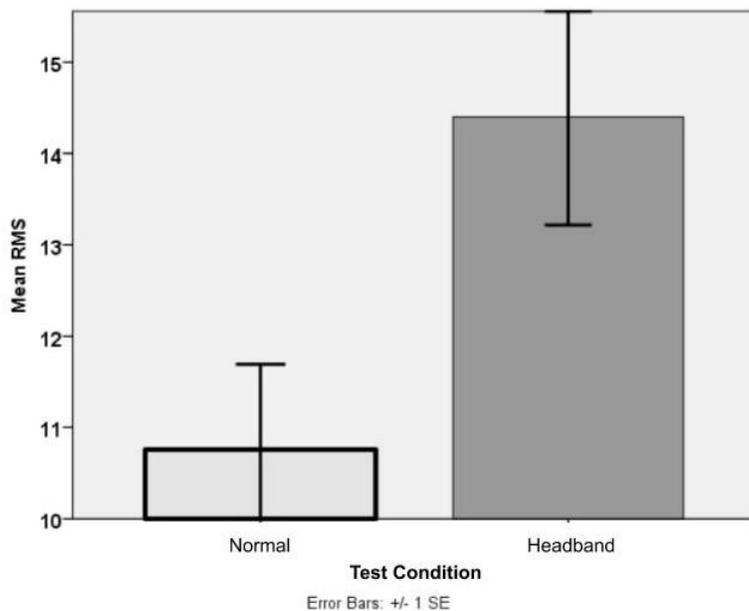


Figure 4. Combined localization error (RMS) from UVA and JMU

While there is clearly a significant effect of the headband as seen in Figure 4, there is considerable variability. The subject to subject differences are more clearly seen in

Figure 5 where each subject is a different line, and summarized in Figure 6, a box plot. As would be expected, individuals tended to have a lesser degree of error in the trial without the headband, resulting in upward sloping lines (Figure 5).

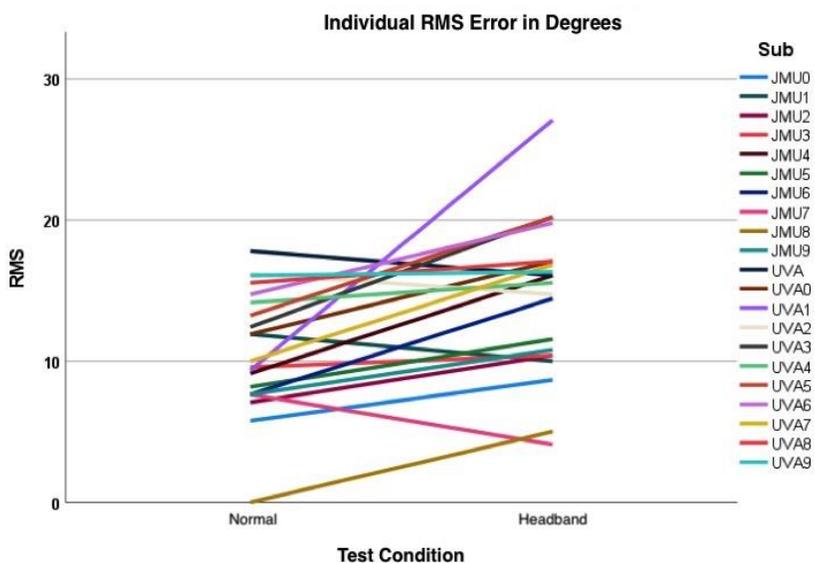


Figure 5. Individual RMS Error in Degrees. Plot of individual participant's RMS degrees of error with and without the headband.

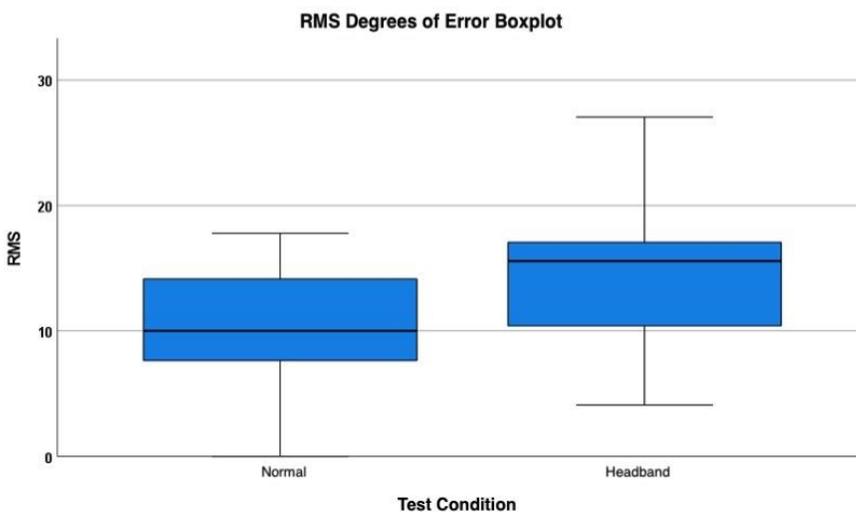


Figure 6. RMS Degrees of Error Boxplot.

A paired samples T test comparing the percent of correct judgments in the control and test conditions (with and without headband) revealed a significant p-value of .001 for JMU and UVA data combined (Figure 7). As expected, participants made more correct predictions of speaker origin when their pinnae were undisturbed (normal) compared to when wearing the headband.

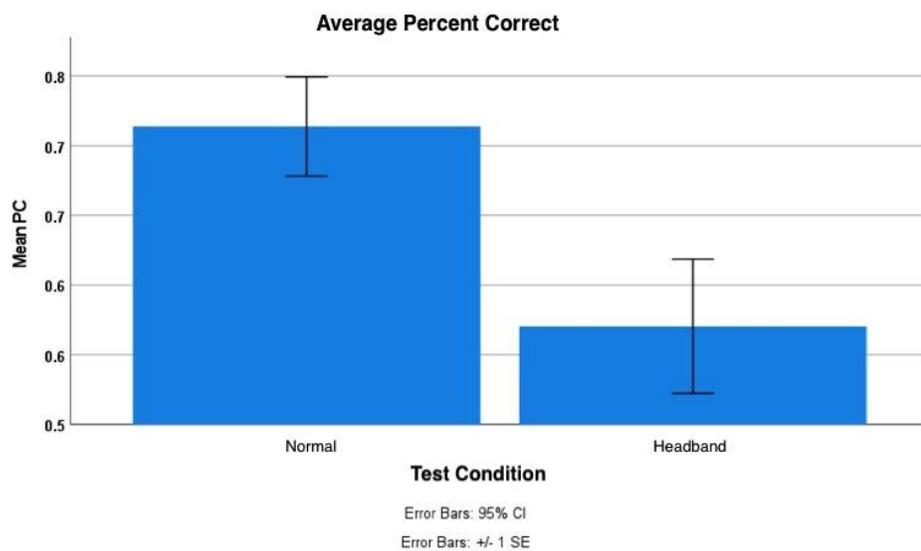


Figure 7. Average Percent Correct. This bar graph represents the average percent correct in each test and control conditions.

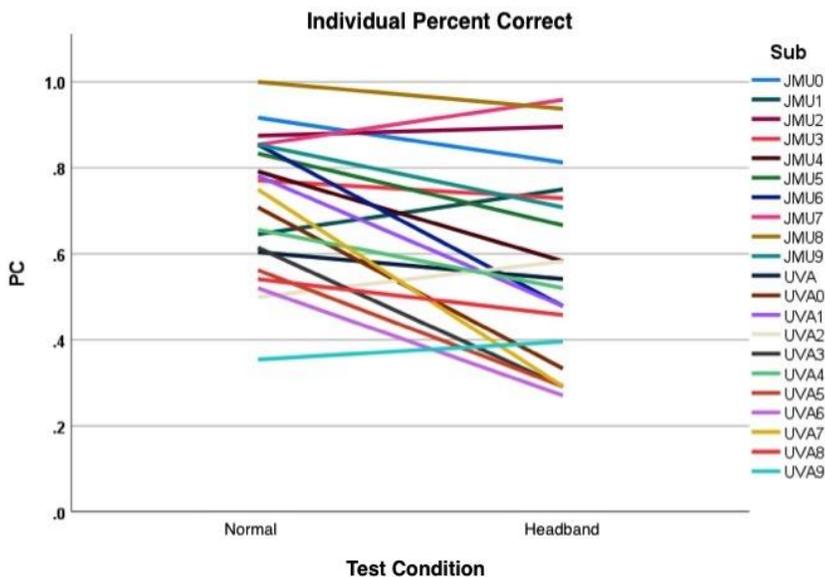


Figure 8. Individual Percent Correct. Plot of each JMU and UVA participants' percent of correct judgments with and without the headband are plotted above. Generally lines trend downwards indicating a decrease in correct judgments when wearing the headband.

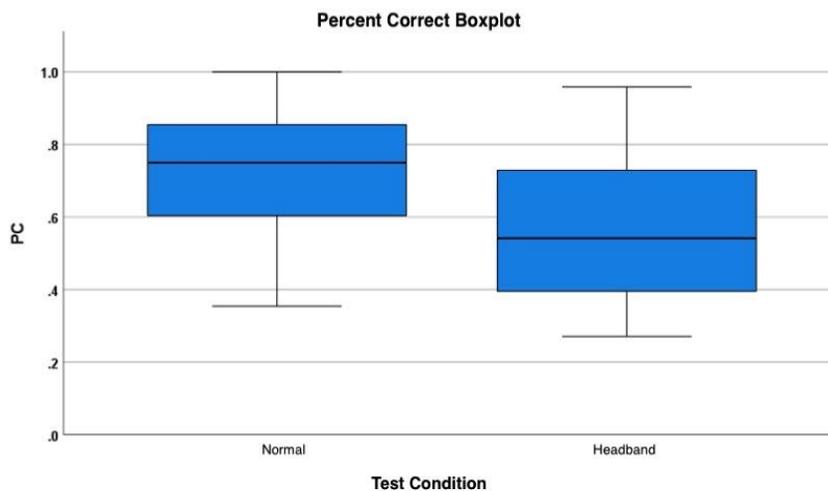


Figure 9. Percent Correct Boxplot.

Individuals typically made more correct judgments without the headband than with the headband, creating a general trend of downward sloping lines (Figure 8). A few

individuals performed more poorly without the headband than with the headband, represented by the upward sloping lines. Figures 5 and 8 help demonstrate the differences between listeners in regards to overall performance and effect of the headband on performance. For example, participant JMU 8 had better overall performance than other participants, as they did not misjudge any trials in the normal condition. Thus, they are plotted at the top of the graph for percent correct and at the bottom of the graph for RMS degrees of error. It is also apparent some listeners were more greatly affected by the change in auricle projection than others, evidenced by the sharply sloping lines in both plots.

None of the five anatomical measurements of auricles from the side or back (Figure 3) correlated with either normal accuracy or change in accuracy with the headband. For example, the strongest correlation ($r = -.35$, $p = .29$) was between width and localization accuracy with no headband. Since there were 10 correlations, a Bonferonni correction for multiple comparisons would mean only $p < .005$ ($.05/10$) would be significant.

Distance from the middle of pinna to the temporal bone (arrow "B" on the right of Figure 3) was $1.5 \pm .5$ cm, providing an estimate of how far the pinna was displaced by the headband. The average width from meatus to the back of pinna in the side view was 2.6 cm yielding an estimated projection angle of 29 degrees.

Chapter V

DISCUSSION

Combining data from both experiments, the effect of the headband pushing the helix against the temporal bone (reducing auricle projection approximately 15 mm or 29 °) is highly significant ($t_{20}= 3.6$, $p= .002$; $d= .9$) and repeatable.

There was no effect of order in the UVA protocol; there was not a significant difference in RMS error between the first and last normal tests ($t_{10}=.002$, $p=.999$). There was also no significant effect of order in the JMU protocol; that is, the difference between RMS error with altered and unaltered auricle did not differ depending on which test occurred first ($t_8=1.58$; $p=.15$). This suggests there was not a learning effect in either experiment.

In the UVA protocol, the tests with a foam earplug in one and then the other ear resulted in RMS errors that were different than normal with an effect size of 5.5. This result is expected, as asymmetrical hearing losses create considerable difficulty in localization (Kumpik & King, 2019). Though highly significant, the effect of the headband is minor compared to inserting an earplug; the headband had only 15% of the effect of a unilateral earplug in terms of increase in RMS error (Figure 6).

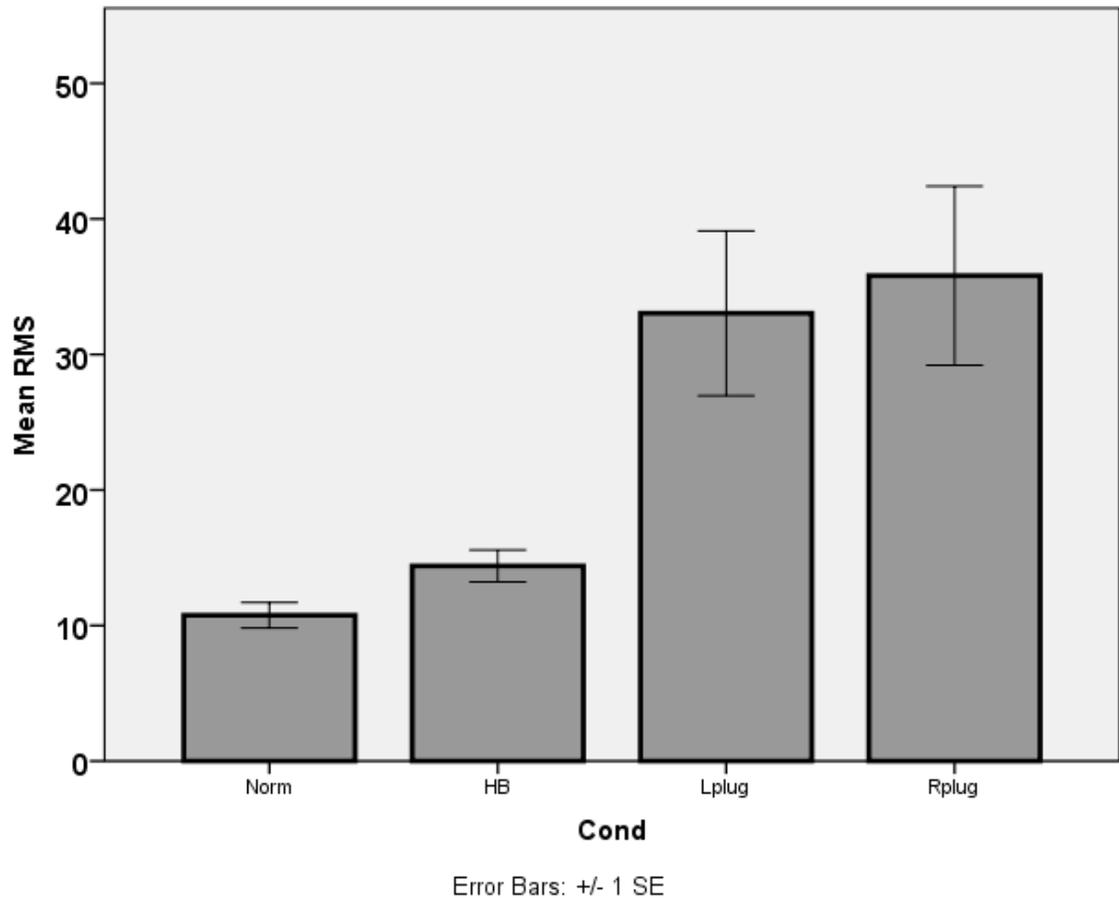


Figure 10. RMS error comparison of all conditions. The mean error in localization (mean RMS) is graphed for normal conditions (Norm), headband conditions (HB), and trials with the left and then right ear plugged (Lplug and Rplug, respectively).

Considering the direction of error (mean error, not just RMS error), there is also more effect of the plug than the headband, as expected. The analyses of accuracy above (RMS error) consider only the magnitude and not the direction of the error, but in the following analyses direction was evaluated. In both protocols there was no consistent direction of error ($p = .82$ and $.32$ in the UVA and JMU protocols respectively, $d = .06$ and $.3$ or 'small'), meaning that errors were made equally in both directions. In contrast, in the UVA protocol when each ear was occluded with an earplug (test conditions 2 and 3),

errors were toward the unplugged ear as expected (Blauert, 1982) with a mean error of 34 degrees. When wearing the headband, however, errors were equal in both directions with a mean error of 0.14 degrees \pm 2.4 SD (Figure 11).

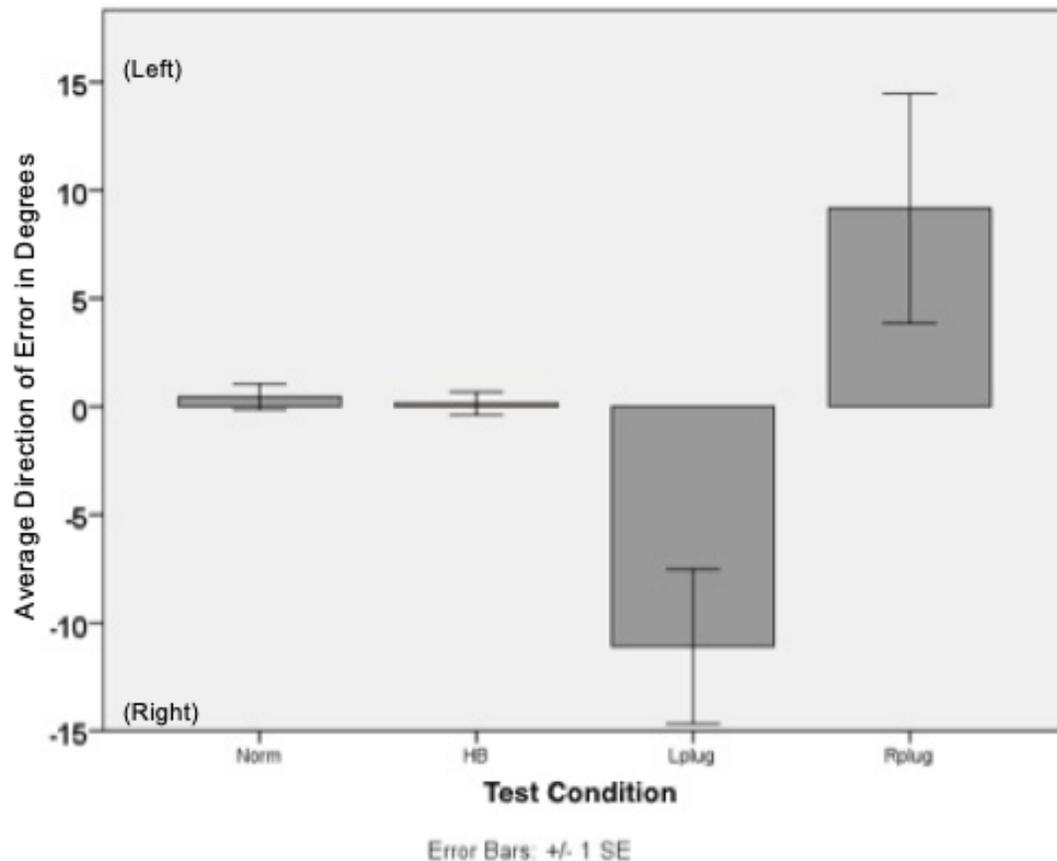


Figure 11. Direction of Error. The direction of error is observable for all four conditions tested.

The negative mean error indicates localization errors to the right while positive mean error indicates localization errors made to the left. This figure uses the data from JMU and UVA for the normal (Norm) and headband (HB) conditions. Only the UVA data was used for left ear plugged (Lplug) and right ear plugged (Rplug) conditions as these conditions were only performed at UVA.

There was a significant difference between the two protocols. Better overall performance (normal and headband conditions) was seen in the JMU protocol. This could

be attributable to the participants being practiced listeners as they were audiology students currently in a psychoacoustics course. In addition, the 8-speaker array was in the middle of a large audiology research room, not adjacent to any walls as in the UVA protocol. The reflections of sound waves bouncing off walls could have added difficulty to the task for the participants at UVA. Also relating to the test environment, the UVA protocol was carried out in a busy ENT clinic, likely having a higher background noise and more potential for distractions than in the test environment at JMU. The similar effect of the headband (in paired comparisons) given different overall localization abilities of each group of participants and separate locations suggests a robust effect of the headband.

Surgically medializing the auricle (otoplasty, “pinning the ears”) is often done to improve perceived aesthetic ‘beauty’. Here we show this has a possible functional implication. Evolution likely favors correlation between form and function in facial features. Subtle alterations in the size and shape of the lips, nose, eyelids, and ears can create readily noticeable changes to a person’s face. Facial plastic and reconstructive surgeons learn to balance desired changes in shape with functional implications. This balance is well studied in the practice of rhinoplasty where aesthetic changes to the nose can compromise the nose’s function, nasal airflow. Functional implications of surgery on the auricle, however, be it otoplasty, microtia repair, or reconstruction after skin-cancer excision, are rarely discussed. This data show a significant functional effect of subtle pinna displacement.

Adaptation

The time-course of adaptation to the altered pinna position is not known. It is certainly possible that with time and practice, sound localization improves after altering auricular projection. Long-term studies were not done. In addition, there was no feedback in any condition. It is quite possible that adaptation would be rapid with feedback or with time as ear mold studies have shown such improvement (Hofman et al., 1998; Van Wanrooij & Van Opstal, 2005; Trapeau et al., 2016).

Four additional subjects were tested at JMU in February of 2021. They each performed the test four times over the course of approximately 20 minutes. The first test was conducted without the headband, and the second test was conducted immediately after putting on the headband. Participants were instructed to continue wearing the headband for 15 minutes while listening to music, slowly walking around the room and swiveling in a chair. This allowed participants to experience various sounds from a variety of known locations, giving them a chance to possibly adapt to their new pinna cues. After 15 minutes, participants repeated the test while still wearing the headband. After test three, participants immediately removed the headband and performed the test for a final time in the 'normal' condition.

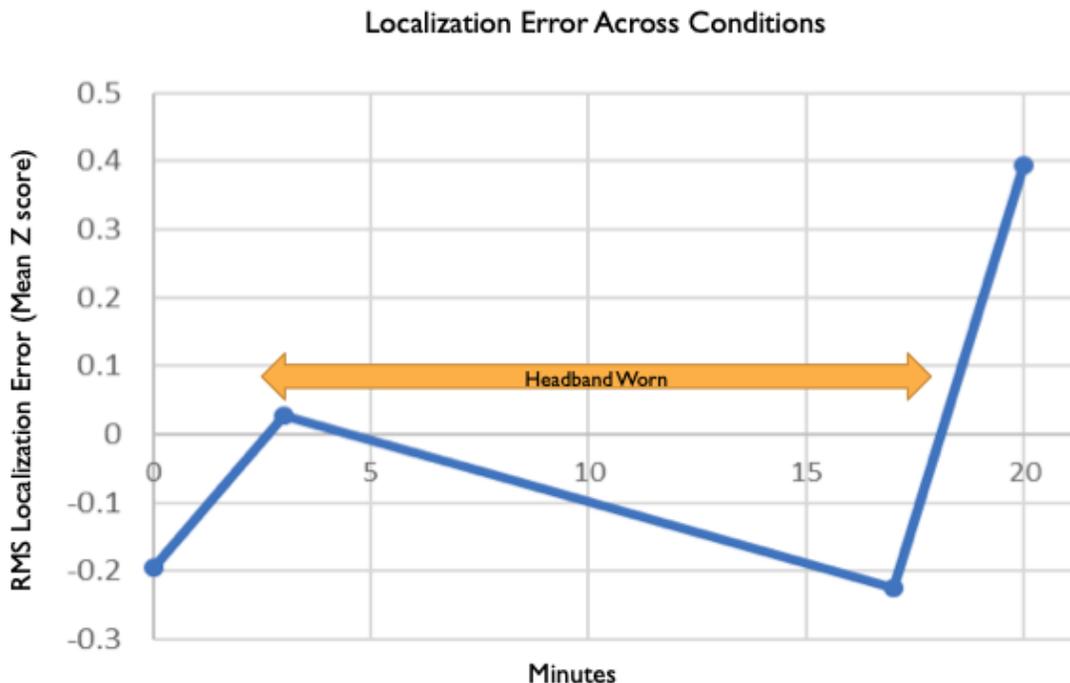


Figure 12. Localization Error Across Conditions. Mean Z-score of RMS of localization error is plotted over a 20 minute time period, during which the test was completed four times.

Some subjects localized better than others, so all results were normalized to four Z-scores for each subject. A Z-score of zero is the average RMS for each subject. This allows comparison of performance between conditions despite variance of listeners. Figure 12 above plots the performance in 4 tests over the 20 minute testing period. The first test (without headband) is at time zero. Listeners performed better than average in this condition indicated by the negative z-scores. Performance of the second test is plotted at the average time stamp of when listeners put on the headband and immediately began the test ($t = \sim 3.5$ minutes). Localization got worse immediately after wearing the tiara, replicating results of the two previous experiments. After the second test, listeners continued to wear the headband for 15 minutes as described above then took the test for a third time ($t = \sim 17$ minutes). On average performance improved back to baseline after the

15 minutes of exposure to binaural sounds from known azimuths. This suggests that 15 minutes of experience with feedback is sufficient to learn the new slightly altered HRTF. Test four was completed immediately after the headband was removed and localization errors increased. This demonstrates another immediate effect on localization, a rebound effect, as errors increased once switching back to the original HRTF (no headband).

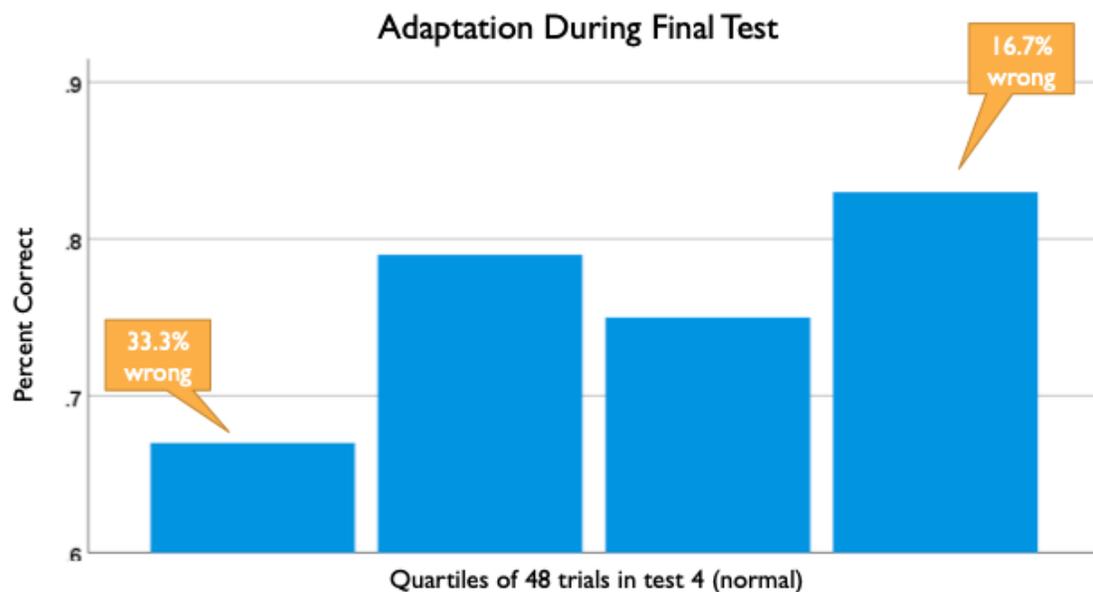


Figure 13. Adaptation During Final Test.

Performance throughout the last test, without the headband, was examined by dividing the 48 noise bursts into four quartiles (Figure 13). The first quartile represents trials (i.e. noise bursts) 1-12; the fourth quartile consists of trials 37-48. On average the percent correct increased throughout testing. The median percent correct from the other normal data is reached after a few trials. There is exactly half the number of incorrect trials in last 12 trials of this fourth test compared to the first 12 trials. This suggests the rebound effect mentioned above is likely quickly corrected even without feedback. That is, removing the headband had an immediate effect on localization error, but listeners adjusted back to their 'normal' HRTF while taking the final test.

Limitations

Limitations of the study included no long-term testing as noted above. A time course for adaptation could certainly exist where participants would improve with time and practice. The studies were done in a quiet, but not soundproof room. It is possible that any small ambient noise could have interfered with testing. Study participants were of varied height; the ears could have been closer or further to the speakers between subjects depending on height. Head movement was also not controlled, though participants were instructed not to move their heads during testing. A small shelf or strap on a stand on which participants could place their chin could have helped to control both head height and movement. Vertical sound localization was not tested. A speaker array that allowed for evaluation of localization accuracy in the vertical and horizontal planes would be ideal. It would not be surprising to find a larger effect of the headband on localization accuracy in the vertical plane. Interaural time and intensity differences are thought to predominate for horizontal sound localization, so the effect reported here was unexpected. The effect on vertical and front-back localization should be greater as spatial cues are the only cues for localization in these dimensions. Lastly, a speaker array in which the speakers were mounted, instead of sitting on a table, would create a more realistic listening condition.

Implications for future research

The effect reported in the present paper could be greater if there were any existing hearing impairment including typical elderly (Hausler, Colburn, & Marr, 1983; Noble,

Byrne, & Lepage, 1994). Recruiting participants of varying ages and degrees of hearing loss may reveal even larger effects of reducing auricle projection.

The effect of any change in pinna position could be greater for a unilateral listener, since without binaural cues, spatial cues would be used to perceive the azimuth of sounds. Changing monaural cues causes large errors in horizontal localization in patients with corrected unilateral congenital aural atresia, for example (Slattery & Middlebrooks, 1994; Wilmington, Gray, & Jahrsdoerfer, 1994; Cole, 2009; Rothpletz et al., 2012).

Sound localization is one of the fundamental benefits of binaural hearing (Avan, Giraudet, & Buki, 2015). The “real world” implications for this study are difficult to quantify but may ultimately affect any situation where binaural processing is important, such as hearing in noise, sports performance, recreational activities, and crossing the street.

Clinical Implications

It is quite possible that auricular surgery does not alter long-term hearing function to a clinically significant degree. Subjective effect on localization could also be minimal, despite the objective data showing localization error. Further research is indicated to establish the time-course of recovery (which might be as short as minutes) and whether any additional concern about altered binaural processing is warranted for those with hearing loss, the elderly, youth, or maybe military service members where front/back and up/down localizations might be critical. Just as the art of rhinoplasty became intimately

related to nasal function, we need to consider the functional implications of surgery on the auricle.

Chapter VI

CONCLUSION

That there was a significant effect of the headband given different overall localization abilities of participants and test environments between protocols indicates a robust effect of the headband. Though the effect of the headband compared to an asymmetrical hearing loss is minor, the combined results still indicate a highly significant effect of the headband. This suggests reducing auricular projection, such as that performed in otoplasty surgery, negatively but significantly impacts horizontal sound localization ability. Therefore, changes in sound localization should perhaps be considered in the consent for otoplasty.

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