GET YOUR EARS DANCING: EVALUATION OF A NOVEL TRAINING PARADIGM FOR POSTERIOR AURICULAR MUSCLE CONTRACTION IN RESPONSE TO AUDITORY STIMULI

by

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Dalhousie University is located in Mi'kma'ki, the
ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Background: Humans have lost the ability to voluntarily direct our ears but still retain the musculature around the ear to do so. A complex of 4 muscles around the ear have been shown to activate in response to shifting attention in both auditory and visual tasks despite the relatively locked position of the ear. This correlates to sustained electrical activity around the ear following attention-drawing stimuli. The purpose of this study is to assess the ability of study participants to develop and use these muscles as both a reflexive and trained response to auditory stimuli.

Methods: A novel auditory auricular myogenic training paradigm was developed for this study. Ten participants underwent 5 training sessions comprised of a facilitation and skill acquisition phase. Through tones-in-noise tasks and coordinate response measure speech-in-noise tasks, participants trained the intentional and lateralized activation of the posterior auricular muscle to auditory stimuli in a virtual auditory space.

Results: Of the 10 participants, 7 were able to obtain some degree of significant improvement in intentional PAM contraction ipsilateral to an auditory stimulus regardless of previous ability or auricular favouring. Correct and reliably lateralized intentional contraction was achieved in 8 participants, but no participant showed a training effect for reflexive posterior auricular muscle activation to high SNR non-speech stimuli.

Conclusions: Intentional manipulation of the posterior auricular muscle was found to be highly trainable for both magnitude of contraction and lateralization in the majority of participants in as few as 5 exclusively auditory-based training sessions. This study increases the toolkit for training the vestigial auriculomotor neural pathway for novel and complex functional activity. Proposed here are potential technological developments into electromyographically controlled vehicles for those with mobility issues, augmentative and alternative communication devices for those with speech and language dysfunction, and intentional directionality in hearing aids for those with hearing loss.

LIST OF ABBREVIATIONS USED

CRM	coordinate response measure
EMG	electromyography(/-myographic)
PAM	posterior auricular muscle
PAMR	postauricular muscle reflex
sEMG	surface electromyography(/-myographic)
SNR	signal-to-noise ratio

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CHAPTER 1 INTRODUCTION

Human ability to spatially direct auditory attention is largely lost with increasing levels of hearing loss and when the sense is directed by a hearing aid or other amplification device (Neher et al., 2009; Petersen et al., 2017; Dai et al., 2018). While technology has allowed for significant improvements in quality of life for those with hearing loss, it fundamentally removes the human aspect of listening – technology cannot effectively determine what and where an individual *wants* to direct their attention, especially in challenging listening environments. Hearing in noise is a strenuous act made increasingly more difficult by degree of hearing loss and reliance on technology. While dramatic improvements in amplified hearing in noise have been made, desired rather than simply directed listening represents an untapped development in hearing aid technology. This study attempts to engage in this field by co-opting a vestigial neural pathway to allow individuals to intentionally manipulate their ears for improved listening in noise.

The human pinna has developed a relatively fixed position on the head as opposed to the highly mobile pinnae seen in other mammals. The auricular muscle complex consists of 4 distinct muscles groups: the posterior, superior, anterior, and transverse auricular muscles (Figure 1.1). Most frequently studied are the pinna orientation responses in cats to both visual and auditory stimuli using combinations of these muscles groups. Orientation towards auditory stimuli occurs with short- and long-latency components in relation to stimulus onset (Populin & Yin, 1998). Eye movement towards a target source resulted in long-latency auricular orientation while short-latency components of pinna movement related to stimulus onset of $\leq$ 25 msec and did not require additional eye or head movement (Populin & Yin, 1998). This short-latency auditory pinna orientation response was found to be asymmetric, with greatest responses occurring ipsilateral to the stimulus (Populin & Yin, 1998).

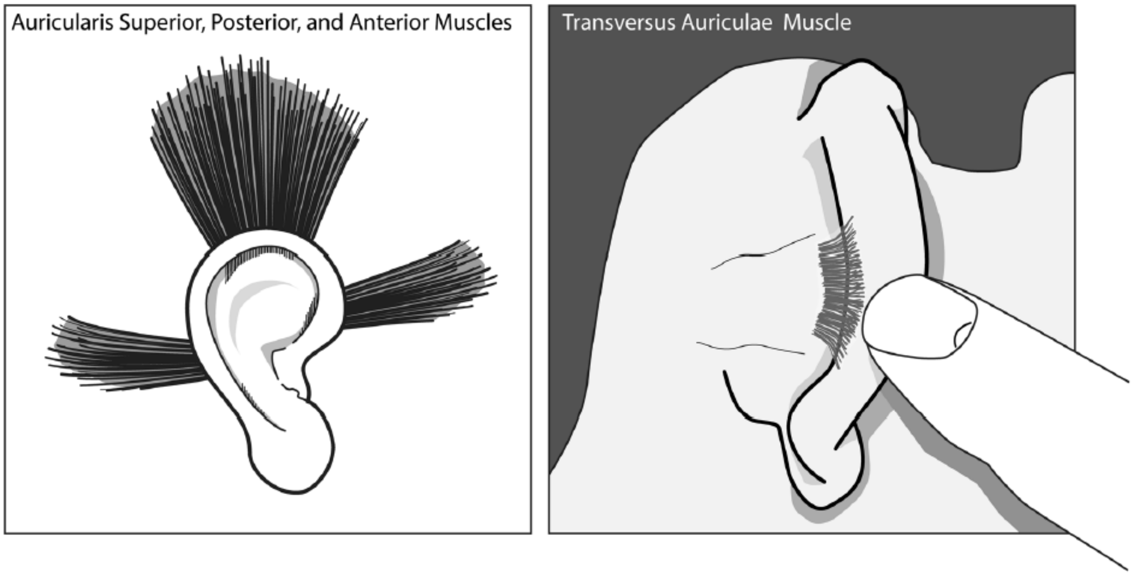


Figure 1.1 Artists recreation of the posterior, superior, anterior, and transverse auricular muscles surrounding the human auricle collectively known as the auricular muscles complex. Image taken from Hackley (2015).

While functional pinna orientation does not occur in humans, Hackley (2015) provided evidence that the postauricular muscle activated in response to novel stimuli through both electromyographic (EMG) and physical reflexive action. Such action represents a ‘neural fossil’ linking physiological reflex with non-functional responses in modern humans. Hackley et al. (2017) further found that the postauricular muscle reflex (PAMR) was not inhibited by visual stimuli and, importantly, was resistant to habituation in both the short and long term. The PAMR can be elicited with relatively low stimulus levels of ~ 35 dB SPL indiscriminate of positive or negative emotional states (i.e. vestigial reflex pathways do not associate with defensive or appetitive intention in humans) (Fox et al., 1989; Hackley et al., 2017; Yoshie & Okudaira, 1969). Additionally, the PAMR has a relatively short 90% refractory period of ~ 90–100 msec (Fox et al., 1989). The PAMR thus represents a weak yet reliable myoelectric response to auditory stimulation present in modern human neural circuitry which has yet to be harnessed for functional purposes.

Recent studies have concluded that, similar to PAMR in cat pinna orientation, human PAMR is also activated asymmetrically in favour of the side ipsilateral to auditory stimulation. Markotjohn (2020; 2023) found evidence for postauricular muscle activation in a spatialized listening task in soundfield and in a virtual auditory space indicating that the PAMR may play a (vestigial) role in auditory attention in humans. The auricular muscle complex has distinct activation patterns according to auditory source localization. Transient auditory stimuli evoked posterior, anterior, and transverse auricular muscle activation but no activation of the superior auricular muscle was detected (Strauss et al. 2020). Sustained, goal-oriented listening altered this outcome by activation of the superior auricular muscle and inactivation of the transverse auricular muscle (Strauss et al. 2020). In both cases, posterior and anterior auricular muscles showed the greatest electromyogenic magnitude of activation of the auricular complex particularly when the auditory stimulus was located ipsilateral and posterior to the target (Strauss et al. 2020). These three seminal studies provide the first evidence for auricular muscle complex activation during spatialized listening in humans.

While reflexive auricular muscle activation is a relatively novel field of study, intentional and trained use of the auricular complex has been evidenced for myoelectric control of motorized vehicles for individuals with tetraplegia (Schmalfuß et al., 2016). Posterior auricular muscle (PAM) training has been successfully completed using visual feedback via computer games controlled by surface EMG (sEMG) signals (Chanthaphun et al., 2019; Schmalfuß et al., 2016). Following as few as 5 training sessions, training improved reaction times for contraction and relaxation of the PAM, the maximum contraction rate, and correct unilateral contraction (Schmalfuß et al., 2016). Auricular control training allowed individuals who initially had no voluntary auricular control to increase both amplitude of physical movement of the pinna via posterior and superior auricular muscles and magnitude of sEMG response in 60% of participants (Chanthaphun et al., 2019). Importantly, Chanthaphun et al. (2019) found that amplitude of pinna movement did not correlate to magnitude of PAM sEMG response indicating that the vestigial neural circuitry is intact regardless of physical ability to move the ear.

There is clear evidence for the presence and reliability of an intact neural circuitry for both voluntary and involuntary control of the auricular musculature complex. All studies to date have conducted training solely using visual stimuli, though it has been shown that auditory stimuli result in a greater magnitude PAM activation. The goal of this study was to assess the reliability and magnitude of trained auricular muscle complex activation to auditory stimuli. To explore this topic, four major questions were developed:

1. Do sEMG responses of the PAM alone indicate directional attention to auditory stimuli or is intentional PAM engagement required to mark attention?
2. Can an auditory attention training regime increase the reliability and/or magnitude of *intentional* PAM activation?
3. Can one reliably deduce auditory directionality and selectively activate auricular muscles in the direction of interest?

4. Does auditory training increase *reflexive* PAM activation to directional auditory stimuli?

If sufficient intentional and/or reflexive EMG stimulation can be trained, this would open a new field of directional hearing aid processing using surface electrical stimulation as a marker for auditory attention. Trained control would allow an individual to select in real time their desired direction for hearing aid attention. This pilot study will open this door to future research and technological development for surface electromyographic directional hearing aids.

CHAPTER 2 MATERIALS & METHODS

This study was largely conducted according to previous auricular control work conducted by Chanthaphun et al. (2019), Markotjohn (2020), Markotjohn (2023), Schmalfuß et al. (2016), and Strauss et al. (2020). These studies form the foundation for the theory of voluntary and involuntary auricular muscle complex control as well as provide evidence and framework for the training paradigm assessed in this study.

2.1 Participants

This study was registered with the Dalhousie University Research Ethics Board (File #2022-6438) and was conducted at the Electrophysiology Lab within the School of Communication Sciences & Disorders of Dalhousie University. Participants were recruited through social media and via word of mouth.

All participants were provided with an institutionally approved consent form reviewed and agreed upon prior to initiation of participation and were provided the opportunity to voluntarily withdraw from the study at any point. Financial compensation was provided after each training session to decrease attrition.

All participants were required to undergo audiometric hearing screening prior to participation in the study to ensure normal hearing (thresholds at 500 Hz, 1000 Hz, 4000 Hz of ≤ 25 dB SPL). Participants were required to be above 18 years of age but were not further excluded based on age or gender. While not required as part of the study, participants were encouraged to practice ‘ear wiggling’ on their own time. Similar to Chanthaphun et al. (2019), participants were asked to complete a brief questionnaire after each session to assess comfort and any potential side-effects of training sessions (e.g. muscle soreness, fatigue, frustration). Contrary to Chanthaphun et al. (2019), one’s previous ability to wiggle one's ear was not an exclusionary criterion as this study attempted to assess a randomly selected population for their ability to *increase* auricular mobility with training. Those with self-reported ability to voluntarily manipulate their ears prior to training were noted as 'ear wigglers' and those who self-reported not having this ability were noted as 'non-wigglers'.

A total of 11 participants, aged 21-31 years, were recruited (3 male, 8 female). One participant was excluded due to a failed hearing screening and was offered recommendations for audiologic support. Of the 10 included participants, 5 self-reported as 'ear wigglers' and 5 as 'non-wigglers'; all 10 completed all training sessions (100% completion rate; Table 2.1).

2.2 Training Protocol

As in Chanthaphun et al. (2019), auricular control training occurred in two phases: a facilitation phase and a skill acquisition phase. Activation of the PAM was monitored in real-time for both voluntary and involuntary auricular control via sEMG. Participants were seated without body, neck, or head restriction. A visual of real-time PAM/PAMR activation constituted of rising and falling bars labelled for each ear was displayed on screen (see Section 2.3 for more details).

Research question #1 was assessed during the facilitation phase. According to Markotjohn (2020), auditory stimuli played through insert earphones in a simulated auditory space elicited ipsilateral and unilateral PAM activation. Participants were played a 1 sec 1000 Hz tone at 65 dB SPL at 135° (right) or 225° (left) azimuth and 0° elevation from the target ear while 60 dB SPL speech spectrum noise was simultaneously introduced at 0˚ to promote listening effort. Participants were instructed to listen for the direction of the tone but not to attempt voluntary auricular control at this stage. Participants were asked to select on a computer screen the direction of auditory stimulation to promote mental engagement, though these results were not recorded. sEMG recordings of the posterior auricular muscle were used to assess innate reflexive auricular control by each participant. Tones were played in a random left/right order in 10 one-minute blocks each containing and randomized number of tones with a minimum of 9 samples per side in each minute ($n_{total} \approx 100$).

The second part of the facilitation phase was conducted in an identical manner, with the participant being asked to attempt to voluntarily contract their PAM on the side of the tone stimulus rather than click a button on screen. Instruction included asking the participant to feel as though they were raising their pinna upwards and backwards. sEMG recordings of this contraction were used to assess: (1) activation of the posterior auricular muscle by attempted voluntary control; (2) the reliability of contraction under manual control; (3) the magnitude of contraction; and (4) the reliability of correct localization of the tone as identified by the individual's auricular contraction. This part of phase one was used as evidence for research question #3.

The second phase of training, the skills acquisition phase, attempted to explore research questions #2 and #3. Auditory training was completed via a coordinate response measure task (CRM). A single male or female talker provided a call sign, colour, and number for the participant to correctly select. One additional sentence was played simultaneously in the opposite ear (= noise) with the participant being told which call sign to listen for. All auditory stimuli were presented at a starting point of 65 dB SPL at 135° (right) or 225° (left) azimuth and 0° elevation from the target ear. Participants were given 5 trials to acclimatize to the task and ensure understanding. sEMG responses during the acclimatization were recorded but excluded from analysis.

Auricular myogenic training was completed using the CRM task and voluntary auricular control. The sentence of interest (i.e. the sentence with a designated call sign) was initially played at ± 6 dB signal-to-noise ratio (SNR), making the task challenging but accomplishable. Participants were asked to listen for the three variables of the target call sign and select the correct colour/number combination on a computer screen.

A 65 dB SPL 1000 Hz puretone was played prior to each CRM stimulus at the same azimuth and elevation as the upcoming target sentence. Participants were asked to voluntarily contract their ear (raise their pinna upwards and backwards) on the target stimulus side (i.e. in the direction of the tone). A correct contraction increased the sentence of interest SNR by 12 dB thereby making the task significantly easier (= reward). This was accomplished by raising the target sentence by 6 dB and lowering the competing sentence by 6 dB. An incorrect contraction (i.e. contraction on the opposite side of the target tone) or no contraction resulted in a 12 dB decrease in target sentence SNR (= penalty), via a 6 dB boost to the competition and a 6 dB attenuation of the target. An SNR threshold of 1.20:1 was set as the cut-off value for correct or incorrect side-specific PAM activation as this was found to both account for weak myogenic activation and eliminate random noise-induced triggering of the reward/penalty. This paradigm was repeated with random left/right paired target tone and sentence stimulus delivery in 5 blocks of 20 paired stimuli ($n_{total} = 100$). A participant's correct or incorrect selection of the colour/number combination was recorded but excluded from analysis as correct or incorrect PAM contraction was the variable of interest.

Each participant was asked to complete 5 training sessions at least 1 day apart from each other (Figure 2.1). The initial training session of the skill acquisition phase was completed immediately following the facilitation phase as post auricular fatigue was not a concern (Fox et al., 1989). Following the final training session, participants completed trials identical to the facilitation phase to assess any potential effect of training on intentional and reflexive PAM activation to non-speech auditory stimuli (research question #4).

2.3 Apparatus & Instrumentation

Surface EMG recordings were conducted using circular non-recessed sticker electrodes located posterior to each pinna in the centre of the mastoid bone (parallel with the PAM) to record electromyogenic changes on the skin surface (Figure 2.2) (Farina & Merletti, 2004a; Farina & Merletti, 2004b; Beretta-Piccoli et al., 2019). This muscle represents the largest contributor to auricular control. Reference electrodes were placed on the exterior undersurface of the pinnae and a grounding electrode was placed on the back of the neck.

Recordings were completed and stored using novel computer software designed expressly for this study in LabVIEW (National Instruments). sEMG responses were measured in the 250 msec immediately following 1000 Hz tone stimulation. Magnitude of PAM activation was quantified as the amplified level of the differential activity after the target tone (or cue tone for the CRM), divided by the baseline level of activity (averaged across all time periods without targets in the tone task and the pre-cue silence between sentence and cue for the CRM task). This constituted a baseline-corrected magnitude. Only baseline-corrected data were stored in this study.

Data from both left and right ears were recorded regardless of side of target stimulus presentation. Graphical displays on screen allowed the participants to be able to appreciate variations in voluntary contraction of the PAM in real time.

During tone training, a left and right bar showed the real-time (non-baseline-corrected) level of PAM engagement on each side. The maximum value of this bar was scaled in real time to the maximum level for that sequence. A further two bars were shown on the left and right. The two bars on the far left indicated the running average of the baseline-corrected left and right PAM with a tone presented to the left. The two bars on the far right indicated the running average of baseline-corrected left and right PAM with a tone presented to the right. This allowed participants to track real time engagement of their PAM and to see whether they were preferentially engaging their PAM in the direction of the cue over the course of each sequence (Figure 2.3).

During CRM training, a left and right bar was shown to show the real-time (non-baseline-corrected) level of PAM engagement on each side (Figure 2.4). The maximum value of this bar was scaled in real time to the maximum level measured on that trial, since PAM engagement levels differ across individuals. A second bar on each side showed the running average of the baseline-corrected PAM measured on that side when a tone was ipsilaterally presented. A green light lit up whenever correct engagement of the PAM was achieved on that trial.

All stimuli were routed through a GSI AudioStar Pro™ 2-channel audiometer (Grason-Stadler, Eden Prairie, MN, USA) and presented through ER-3A insert earphones (Etymotic Research Inc., Lucid Hearing Holding Company) in a virtual auditory space.

All auditory target and noise stimuli were calibrated using a 2cc coupler with a Larson Davis SoundTrack LxT1 Sound Level Meter (Type 1 re: ANSI s1.4-1983 (R2006)).

Stimuli were presented at a sampling rate of 40k via a National Instruments 24-bit PXI-4461 Dynamic Signal Acquisition card controlled by a National Instruments PXI-8110 controller with custom software in LabVIEW.

Electrophysiological responses were bandpass filtered between 10 and 1000 Hz (–6 dB/octave for both) and amplified 5000x via an Intelligent Hearing Systems analogue Opti-Amp system. A further anti-aliasing low-pass filter (4th Order Butterworth) at 2000 Hz was applied by the Opti-Amp system before routing the signal to a National Instruments PXI-6281 Multifunction DAQ for digitization at 40k. The clocks of the PXI-4461 and PXI-6281 cards were synchronized to a master clock on the backplane of the PXI-1031 chassis to ensure precise system timing.

2.4 Stimulus Details

Tonal blocks

Tones were 1000 Hz and 250 msec in length, with a 5 msec linear onset and offset ramp. Tones were presented in a virtual sound space at 135˚ and 225˚ by convolution with head-related impulse responses measured with KEMAR (large ear) from the CIPIC data base (Algazi et al., 2001; Andreopoulou & Roginska, 2011). Tones were combined with Gaussian noise at 50 dB SPL, with a 5 msec linear onset beginning at the same time of each tone and offset ramp 250 msec after each tone. The noise was presented without any HRIR filtering.

Sequences of tones were presented with randomized left/right orders and stimulus onset asynchronies ranging from 2250 msec to 3250 msec. Each sequence was constrained to have a minimum of 9 left and 9 right tones over the course of 1 minute. Each trial consisted of ten 1-minute unique sequences.

Sentence Blocks

Two CRM sentences were played to locations in a virtual sound space at 135˚ and 225˚(using the same HRIRs as had been used by tones, as described above) at a starting level of 65 dB A (and adjusted as described above). Each sentence was of the form "Ready <call sign> go to <colour> <number> now." with 8 call signs, 4 colours (blue, red, white, and green) and 8 numbers (1–8). The target call sign was always "Charlie" and was presented randomly at either the left (225˚) or right (135˚) location, while the sentence presented to the opposite ear always had a call sign that was not Charlie (e.g., "Ringo").

Prior to the presentation of each pair of sentences, a cue tone was presented at the same virtual sound location as the upcoming target. Each cue was 250 msec in length with a 5 msec linear ramp and began 1.625 sec following the offset of the preceding sentence. Cues preceded sentences with a stimulus onset asynchrony of 1.375 sec (i.e. a gap of 1.125 sec).

2.5 Data Analysis

All data analyses were completed using R Statistical Software (v. 4.2.1; R Core Team, 2022) and RStudio (v. 2023.12.1; RStudio Team, 2024). sEMG responses were corrected for directional bias by calculating the difference between baseline-corrected PAM level on the auditory target side and baseline-corrected PAM from the opposing ear for reflexive and facilitative intentional data. Directional bias was not corrected in CRM intentional data but was accounted for as a factor within analyses.

All data were assessed for normality using a Shapiro-Wilk test and cross-referenced with visual inspection of Q–Q plots. Descriptive statistics for each participant were derived from pre- and post-training PAM results according to above preprocessing for reflexive and facilitative intentional data and across sessions for CRM intentional data. Means and SDs were computed and used in graphical representation. One-way ANOVA's were conducted on group data without factoring participant as a fixed random variable (package rstatix; Kassambara, 2023). Linear mixed-effect models with restricted maximum likelihood ratio (package lmerTest; Kuznetzova et al., 2022) were used to analyse PAM activation pre- and post-training for reflexive and facilitative intentional data and across training for CRM intentional data. All data were treated as within-subject longitudinally across the duration of participation within the study with PAM activation, session, and cue direction as fixed variables. Participant in all modelling was treated as a random intercept with fixed mean to account for individual variability (Bates et al., 2015). All linear mixed-effects models were described in R as:

Model = lmer(Outcome ~ Predictor + Fixed Effect + (Fixed Effect*Interaction) + + (1|Random Effect), data = Data Frame)

Pairwise t-tests with a Bonferroni correction were used *post-hoc* to assess significance ($\alpha = 0.05$). Visual representations of the data were created with package ggplot2 (Wickham, 2016). All coding used in analysis is available (Appendix A).

2.5 Expected Outcomes

This project was hoping to explore the potential for electromyogenic stimulation in response to spatial listening tasks. The outcome for research question #1 was expected to reinforce research previously conducted by Markotjohn (2020) and Strauss et al.

(2020) indicating that the auricular muscles reflexively activate in response to auditory stimulation in both an ipsilateral and unilateral manner. Auditory auricular training was expected to increase both the reliability and magnitude of correct unilateral activation as previously documented through visual-based auricular training by Chanthaphun et al. (2019) and Schmalfuß et al. (2016) (research question #2). If such training can improve these factors, reliable sound localization should be witnessed and improved through both voluntary and involuntary auricular musculature complex activation (research question #3). Ideally, this improvement would yield an increased magnitude of involuntary auricular musculature complex activation in response to directional auditory stimuli (research question #4). Such advances in knowledge would provide a strong foundation for further study in electromyogenic directional hearing aids.

2.6 Tables & Figures

Table 2.1 Summary of participants recruited for auricular myogenic training paradigm and self-reported ability to voluntarily manipulate auricles (i.e. wiggle their ears) prior to training.

Participant	Age	Gender Identity	Number of sessions completed	Previous ear wiggler?
001	28	F	5	No
002	30	F	5	Yes
003	31	M	0	No
004	31	F	5	No
005	23	F	5	Yes
006	28	M	5	Yes
007	23	F	5	No
008	24	F	5	No
009	23	F	5	Yes
010	24	F	5	No
011	21	M	5	Yes

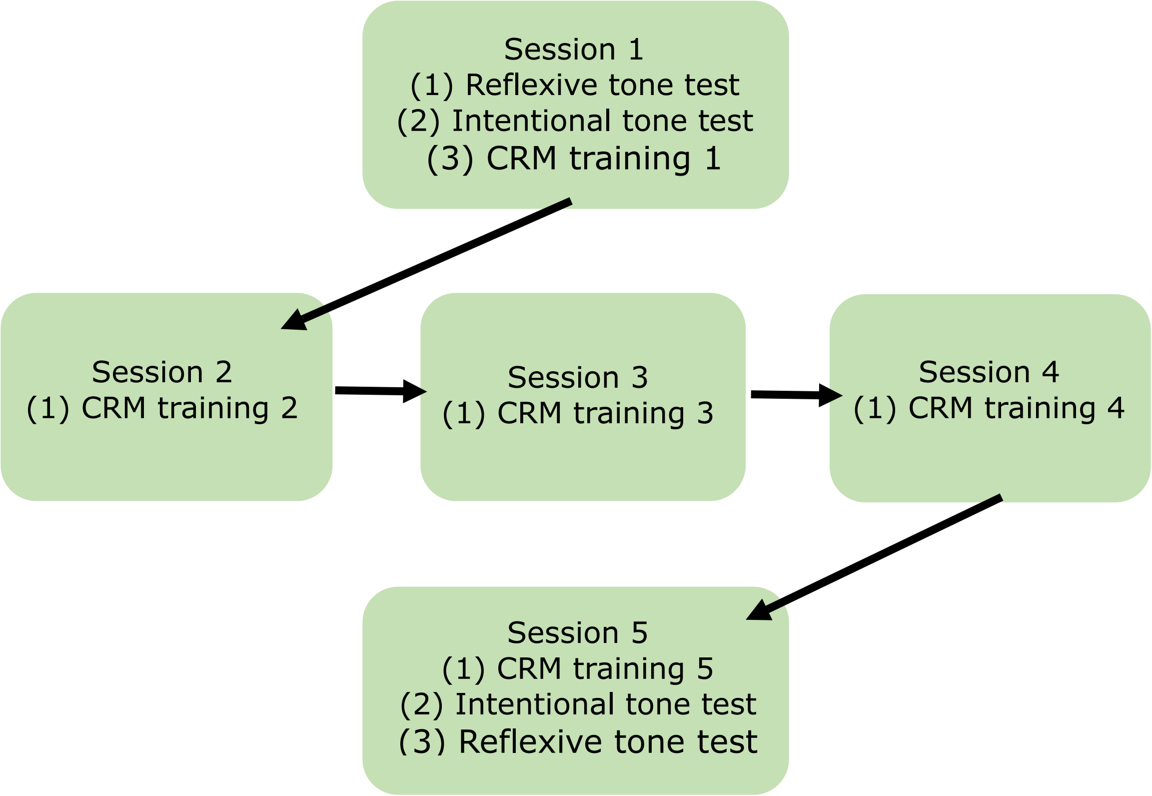


Figure 2.1 Participation workflow for auricular myogenic training paradigm. Each participant was asked to complete all 5 sessions. Reflexive tone testing and intentional tone testing accounted for the facilitation phase and CRM training accounted for the skill acquisition phase.

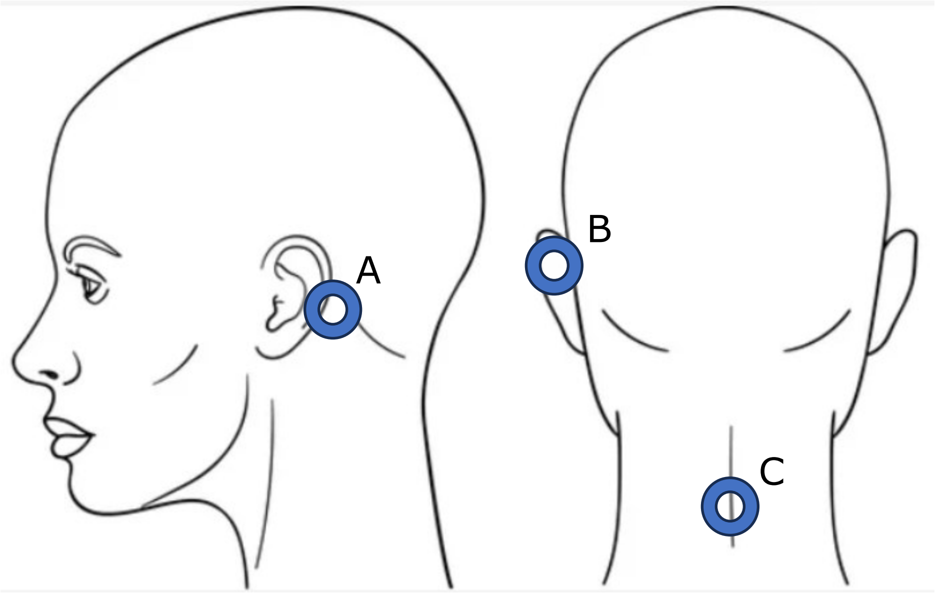
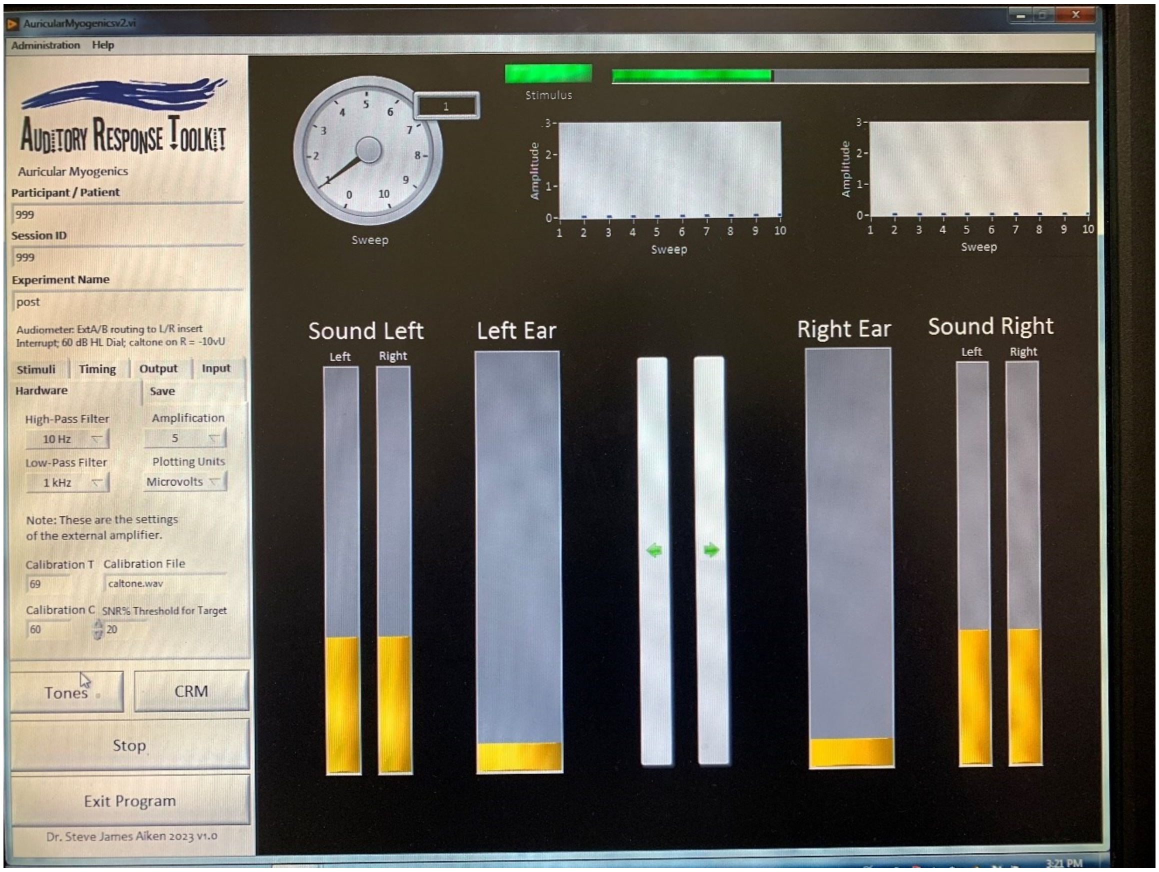
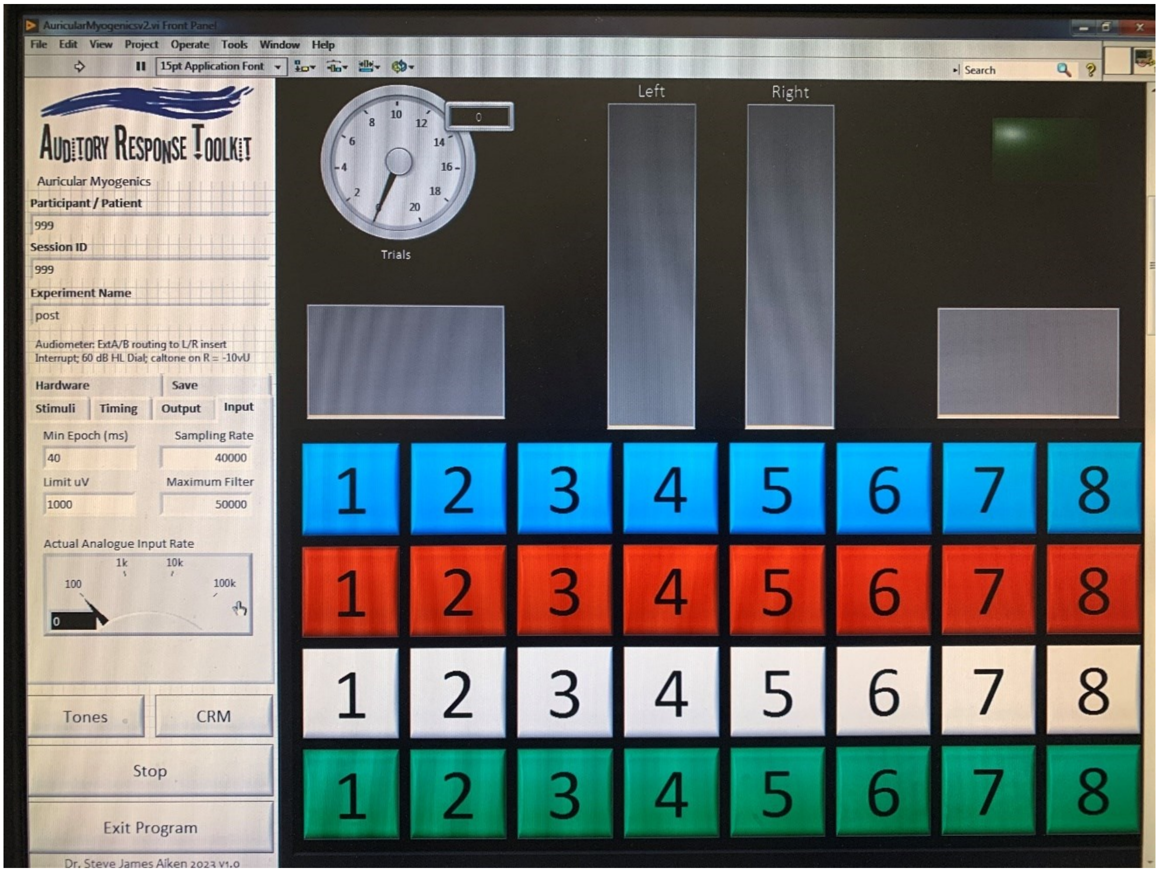


Figure 2.2 Locations of electrode placement for facilitation and skill acquisition phase training tasks. All auricular electrodes were placed bilaterally for all tasks. (A) Active electrode; (B) Reference electrode; (C) Ground electrode. Image courtesy of Begak (2024).



Participant / Patient: 999
Session ID: 999
Experiment Name: post
Audiometer: ExtA/B routing to L/R insert Interrupt; 60 dB HL Dial; caltone on R = -10vU
High-Pass Filter: 10 Hz
Amplification: 5
Low-Pass Filter: 1 kHz
Plotting Units: Microvolts
Note: These are the settings of the external amplifier.
Calibration T: 69
Calibration File: caltone.wav
Calibration C: 60
SNR% Threshold for Target: 20

Figure 2.3 On-screen display seen by participants during facilitation phase tones-in-noise tasks. Yellow bars would fluctuate in height based on real-time sEMG response of the left and right posterior auricular muscles. Participants were asked to either click the arrow or manually manipulate their posterior auricular muscle on the side of tone presentation.



Participant / Patient: 999

Session ID: 999

Experiment Name: post

Audiometer: ExtA/B routing to L/R insert
Interrupt; 60 dB HL Dial; caltone on R = -10vU

Min Epoch (ms): 40

Sampling Rate: 40000

Limit uV: 1000

Maximum Filter: 50000

Figure 2.4 On-screen display seen by participants during skill acquisition coordinate response measure training tasks. Yellow bars would fluctuate in height based on real-time sEMG response of the left and right posterior auricular muscles. Participants were asked to follow the call sign “Charlie” to an associated colour/number combination while ignoring competing speech.

CHAPTER 3 RESULTS

3.1 Coordinate Response Measure Training

Across the 5 CRM training sessions, all participants were able to achieve some degree of intentional activation of the PAM to the auditory stimulus, however the trend of overall improvement with training at the population level was not significant (Figure 3.1; df = 4, F = 1.399, P = 0.232). It cannot be stated, therefore, that at a population level a significant increase in the magnitude of correct PAM activation should be expected through CRM training alone.

Longitudinal improvement between participants was seen when individual variability was accounted for as opposed to at a population level (Figure 3.2). Within participants, a significant difference in PAM activation was seen across training sessions (df = 4, F = 7.226, $P < 0.0001$), magnitude of lateralized contraction (df = 1, F = 9.519, $P < 0.01$), and one's ability to correctly activate the target side (df = 1, F = 19.986, $P < 0.0001$). In order to assess PAM activation through training, the magnitude of correct left-right activation was compared between sessions 1 and 5 (i.e. initial vs. final training session) (Table 3.1). Significant improvement in magnitude of correct PAM activation during training was seen in participants 002 (left ear only), 006 (right ear only), and 007 (bilateral). Interestingly, participant 009 had a significant decrease in left ear activation across training.

It was common for participants to favour an ear which was noted anecdotally by participants and found to be statistically significant for all but participant 004 and 006 (Table 3.2). The side of bias was not predictable with 4 participants favouring the left ear and 3 participants favouring the right ear. Favouring an ear did not affect a participant's ability to correctly activate the PAM to the target side with all but participant 002 and 004 improving in their ability to intentionally and correctly contract the PAM on the target stimulus side (Table 3.3).

3.2 Reflexive PAM Training

At the group level, reflexive PAM activation to an auditory stimulus in a virtual headspace was minimal and did not improve with training (df = 1, F = 2.726, P = 0.0996) (Figure 3.3). No individual participant within this study showed improvement in reflexive PAM activation after training (F = 2.905, P = 0.0892) and most did not favour an ear (Figure 3.4). However, right ear favouring was still seen in participant 004 (df = 19, F = -2.641, $P < 0.05$) and left ear favouring in participant 011 (df = 19, F = 3.779, $P < 0.001$) at the reflexive level. This may suggest a baseline acuity for lateralized activation in these participants.

3.3 Intentional PAM Training

At the group level, auditory auricular myogenic training improved one's ability to intentionally activate the PAM in a direction of interest (df = 1, F = 37.28, $P < 0.0001$) (Figure 3.5). Bilateral improvement was seen in participants 001, 005, 008, and 009 while participants 006, 007, and 010 improved unilaterally (Table 3.4). Participants 002, 004, and 011 did not show significant training effects for intentional PAM activation. Collectively, this indicates that 7 of 10 participants (or 11 of 20 ears) showed significant improvement in intentional and lateralized PAM activation with auditory auricular myogenic training. Interestingly, intentional activation of participant 007's right PAM significantly decreased with training.

Auricular favouring was noted in participants 005, 006, 007, 009, and 010 (Table 3.5). Post-training auricular favouring was conserved in participants 005 and 007, reversed in participant 009, eliminated in participant 010, and increased in participant 006.

3.4 Tables & Figures

Table 3.1 Comparison of lateralized PAM activation between sessions 1 and 5 of CRM training using paired t-tests with Bonferroni correction. * indicates significance.

Participant	PAM side	df	F-value	P-value
001	Left	9	-0.91	1.00
	Right	9	2.52	0.329
002	Left	9	-14.99	< 0.001*
	Right	9	1.73	1.00
004	Left	9	1.65	1.00
	Right	9	-2.13	0.621
005	Left	9	-1.49	1.00
	Right	9	-0.53	1.00
006	Left	9	-0.66	1.00
	Right	9	-3.96	< 0.05*
007	Left	9	-4.59	< 0.05*
	Right	9	4.40	< 0.05*
009	Left	9	3.97	< 0.05*
	Right	9	2.75	0.226
010	Left	9	-3.37	0.083
	Right	9	-3.59	0.059
011	Left	9	-0.96	1.00
	Right	9	-0.30	1.00

Table 3.2 Comparison of lateralization of PAM activation across 5 CRM training sessions using paired t-tests with Bonferroni correction. * indicates significance.

Participant	Directional bias	df	F-value	P-value
001	Left	49	2.80	< 0.01*
002	Right	49	-3.17	< 0.01*
004	None	49	-1.08	0.286
005	Right	49	-5.52	< 0.001*
006	None	49	-0.16	0.874
007	Left	49	3.83	< 0.01*

Participant	Directional bias	df	F-value	P-value
009	Right	49	-7.07	< 0.001*
010	Left	49	4.59	< 0.001*
011	Left	49	3.74	< 0.01*

Table 3.3 Participant ability to correctly activate the PAM to a lateralized auditory cue across 5 CRM training sessions assessed by paired t-tests with Bonferroni correction. * indicates significance.

Participant	Correct activation bias	df	F-value	P-value
001	Yes	49	-5.16	< 0.001*
002	None	49	-0.76	0.448
004	None	49	1.35	0.183
005	Yes	49	-12.58	< 0.001*
006	Yes	49	-2.36	< 0.05*
007	Yes	49	-22.68	< 0.001*
009	Yes	49	-9.72	< 0.001*
010	Yes	49	-11.21	< 0.001*
011	Yes	49	-14.83	< 0.001*

Table 3.4 Improvement in intentional PAM activation to a non-speech based auditory task from pre- auditory auricular myogenic training to post-training. * indicates significance.

Participant	PAM side	Greater PAM	df	F-value	P-value
001	Left	Post-training	9	-4.08	< 0.05*
	Right	Post-training	9	-6.34	< 0.01*
002	Left	None	9	0.21	0.841
	Right	None	9	-0.61	0.556
004	Left	None	9	0.75	0.470
	Right	None	9	0.96	0.361
005	Left	Post-training	9	-16.44	< 0.001*
	Right	Post-training	9	-10.88	< 0.001*
006	Left	Post-training	9	-4.23	< 0.01*
	Right	None	9	1.20	0.263
007	Left	Post-training	9	-10.08	< 0.001*
	Right	Pre-training	9	5.83	< 0.001*
008	Left	Post-training	9	-3.57	< 0.01*
	Right	Post-training	9	-3.74	< 0.01*
009	Left	Post-training	9	-3.43	< 0.01*
	Right	Post-training	9	-12.99	< 0.001*
010	Left	Post-training	9	-4.87	< 0.001*
	Right	None	9	-1.75	0.114

Participant	PAM side	Greater PAM	df	F-value	P-value
011	Left	None	9	-1.05	0.320
	Right	None	9	-2.20	0.560

Table 3.5 Comparison of auricular favouring pre- and post-CRM training when intentionally activating the PAM to a non-speech associated auditory task in those participants for which a significant effect was found using paired t-tests with a Bonferroni correction. * indicates significance.

Participant	Favoured side	Pre-/Post-training	df	F-value	P-value
005	Right	Pre-training	9	-6.61	< 0.001*
	Right	Post-training	9	-4.25	< 0.01*
006	None	Pre-training	9	-1.24	0.245
	Left	Post-training	9	5.53	< 0.001*
007	Left	Pre-training	9	9.40	< 0.0001*
	Left	Post-training	9	11.85	< 0.0001*
009	Left	Pre-training	9	2.98	< 0.05*
	Right	Post-training	9	-5.01	< 0.001*
010	Right	Pre-training	9	-2.46	< 0.05
	None	Post-training	9	1.69	0.125

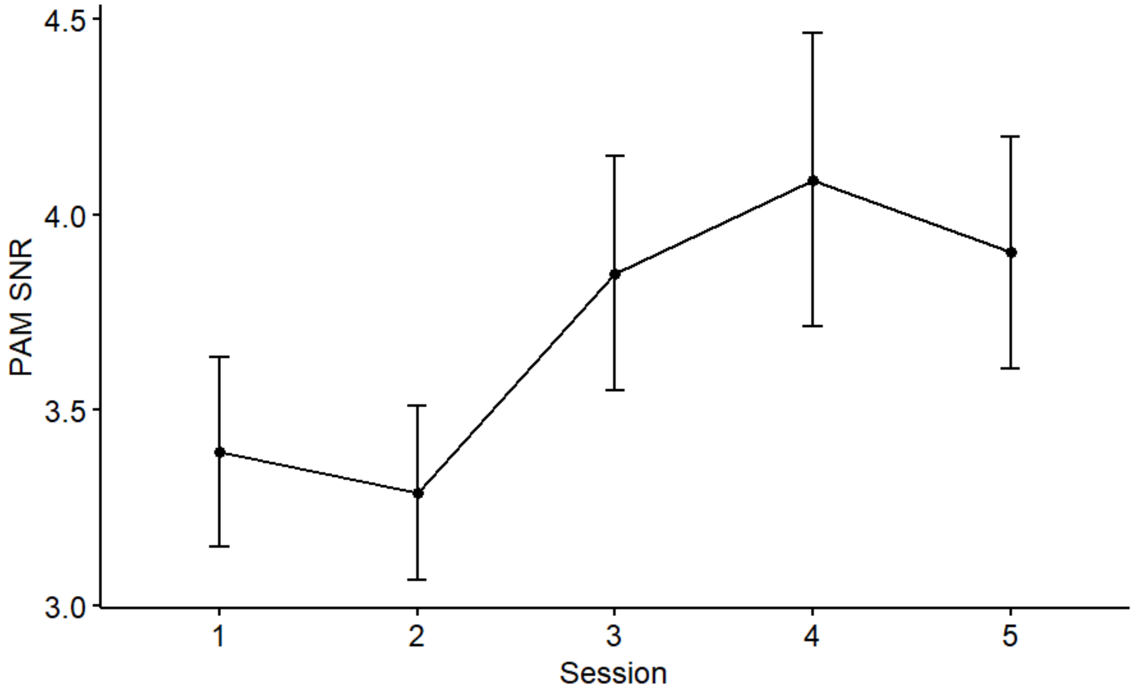


Figure 3.1 Intentional PAM activation over 5 training sessions in response to a 1000 Hz tone immediately preceding a speech stimulus across all participants.

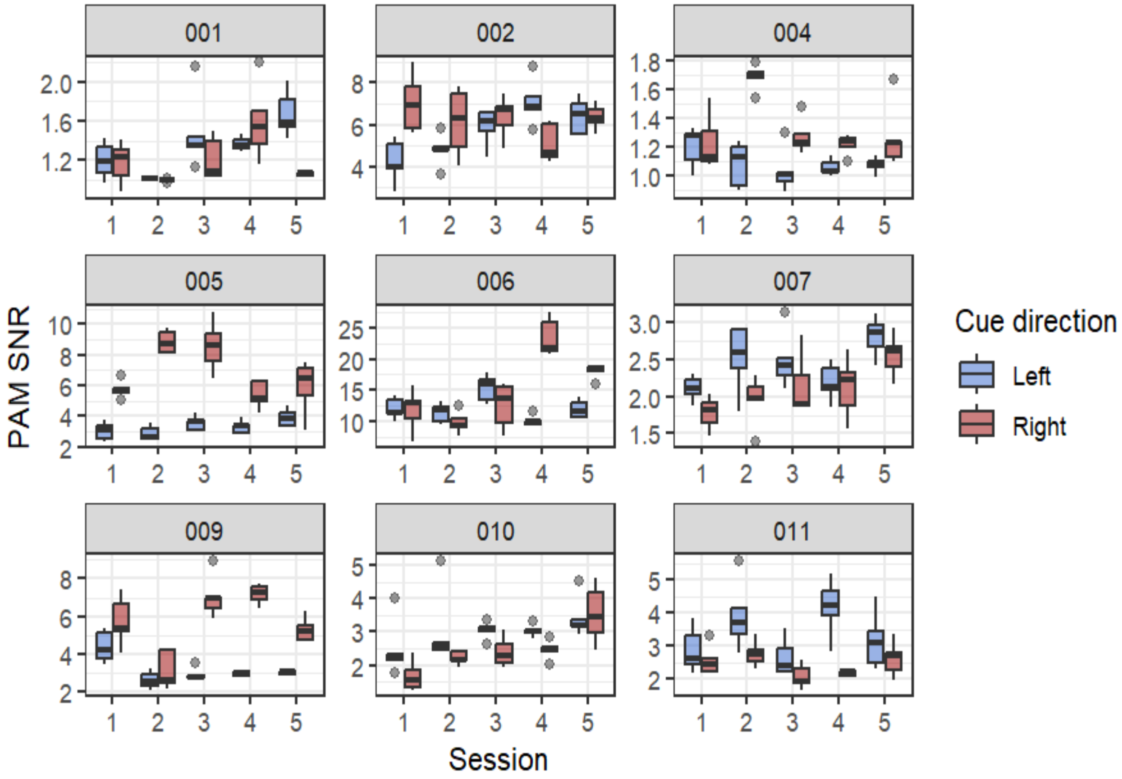


Figure 3.2 Intentional PAM activation over 5 training sessions to a 1000 Hz tone immediately preceding a lateralized speech stimulus. Participant 008 was excluded due to recording error.

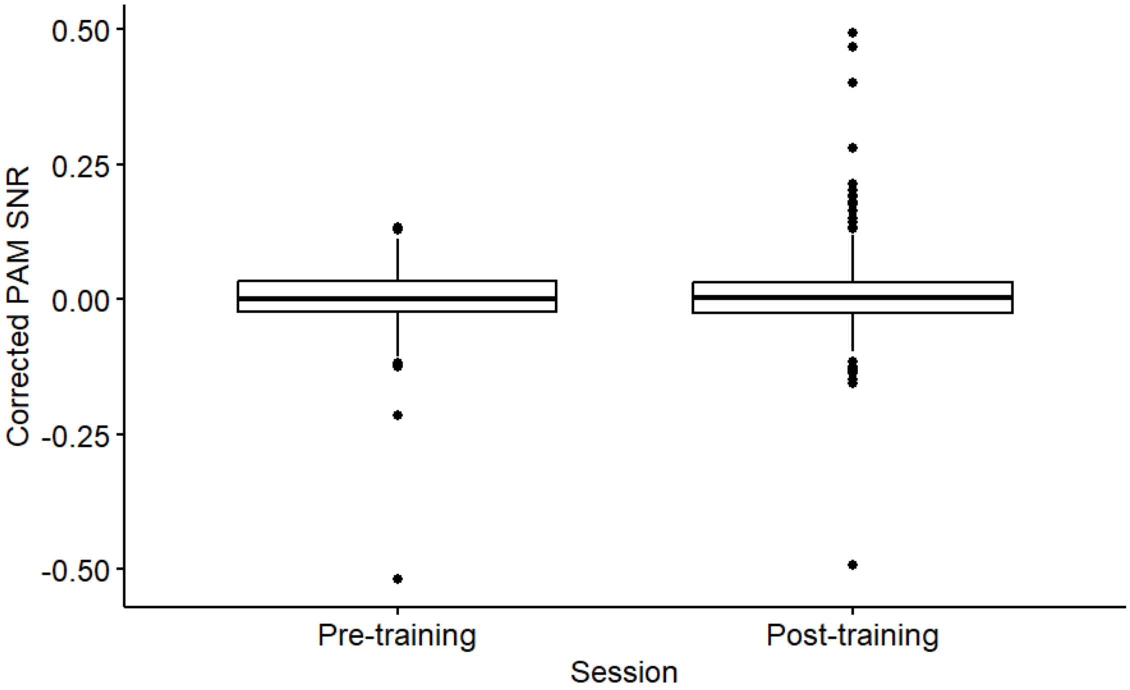


Figure 3.3 Directionally biased reflexive PAM activation across all participants to a lateralized 1000 Hz tone in a virtual auditory headspace before and after auditory auricular myogenic training.

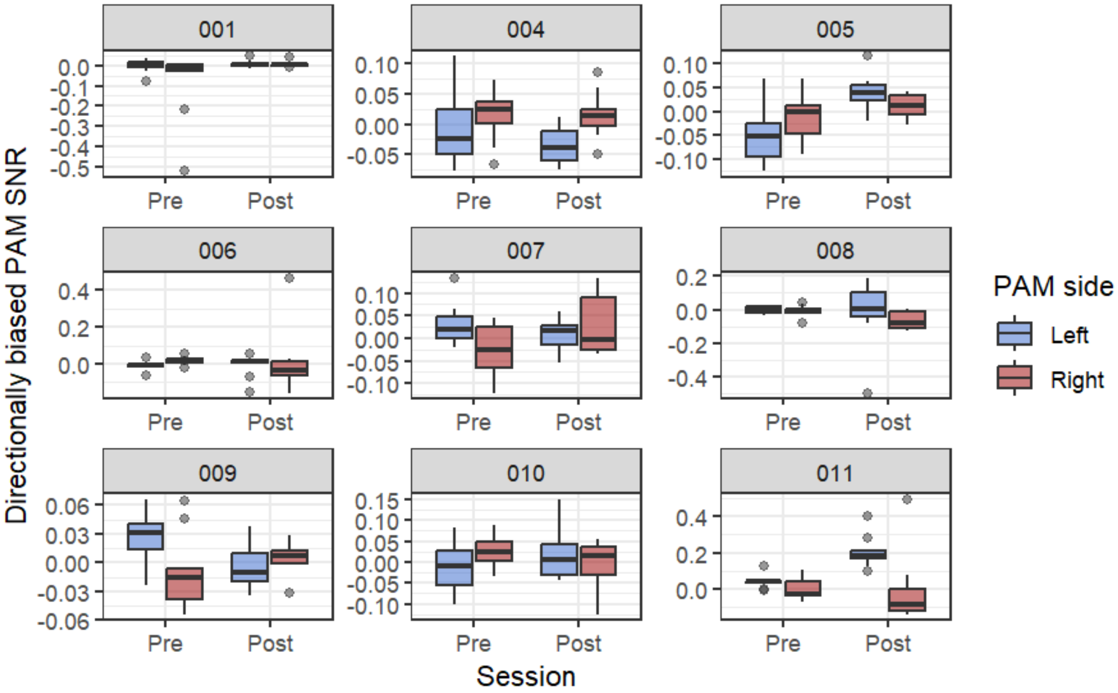
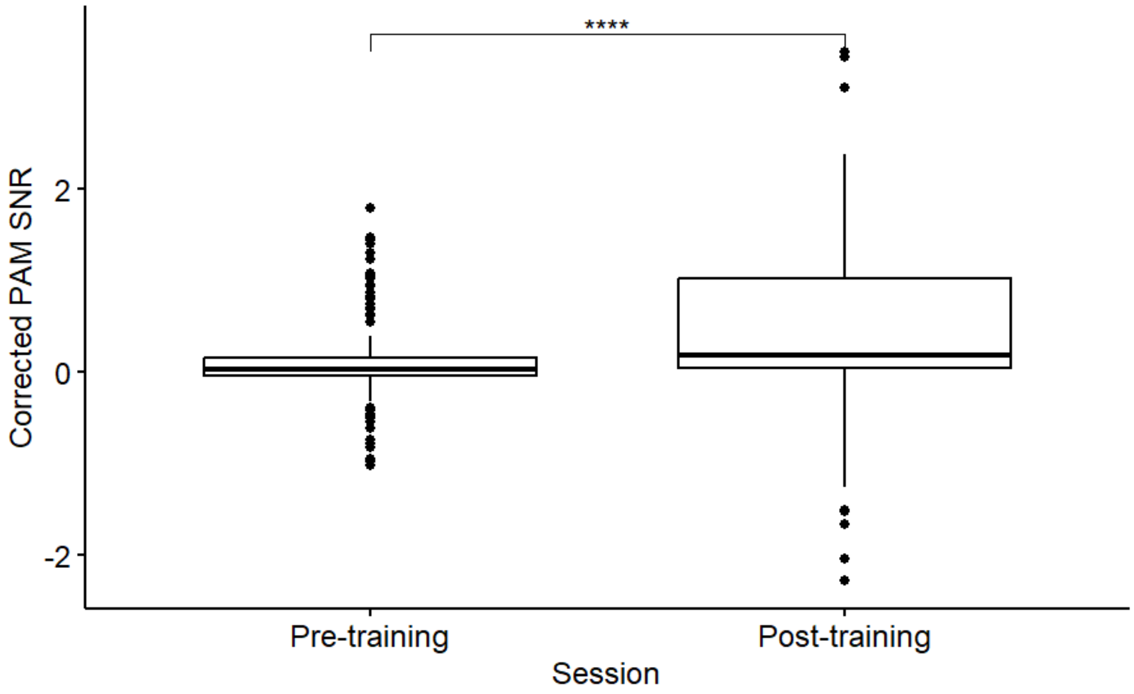


Figure 3.4 Directionally biased reflexive PAM activation to a lateralized 1000 Hz tone in a virtual auditory headspace before and after auricular myogenic training. Participant 002 was excluded due to incompletion of task.



**** = p < 0.0001

Figure 3.5 Directionally biased intentional PAM activation across all participants to a lateralized 1000 Hz tone in a virtual auditory headspace before and after auditory auricular myogenic training. * indicates significance.

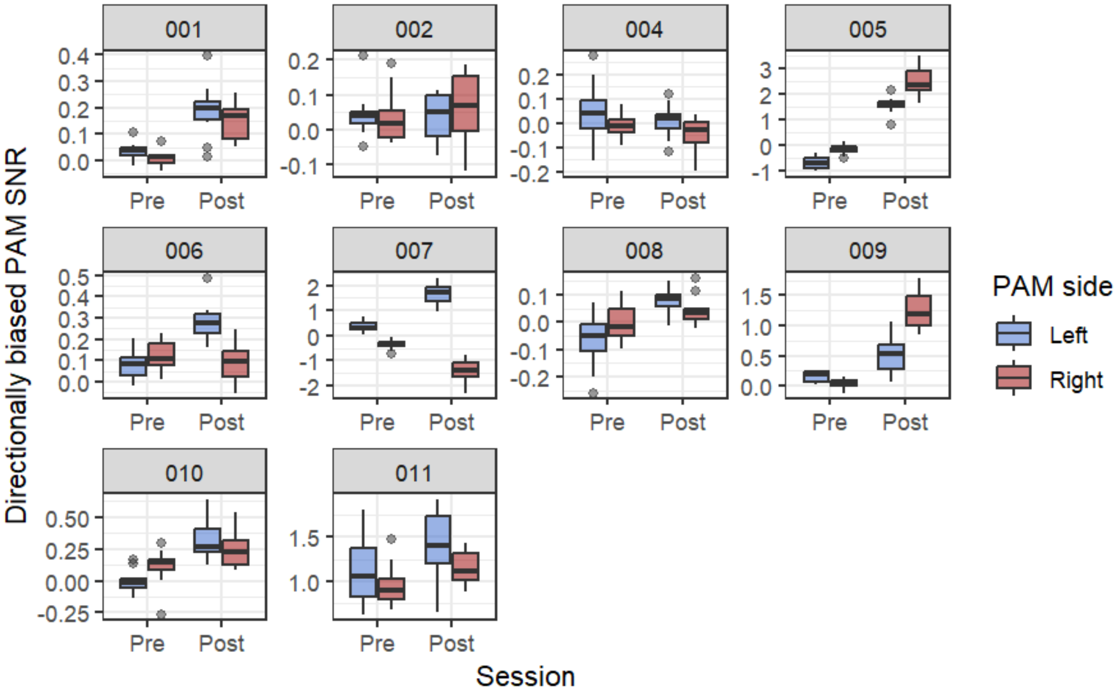


Figure 3.6 Directionally biased intentional PAM activation to a lateralized 1000 Hz tone in a virtual auditory headspace before and after auditory auricular myogenic training.

CHAPTER 4 DISCUSSION

The results of this study indicate that most people have some ability to learn manual manipulation of the PAM through an auditory auricular myogenic training paradigm. Our improvement rate of 70% of participants stands firmly between those of Schmalfuß et al. (2016)'s 100% rate and Chanthaphun et al. (2019)'s 60% rate using visual training paradigms. Collectively, this indicates a high probability of improvement in correct lateralized PAM activation to non-speech stimuli through training.

4.1 Research Question #1

Do sEMG responses of the PAM alone indicate directional attention to auditory stimuli or is intentional PAM engagement required to mark attention?

No effect of training was seen in reflexive PAM activation to lateralized auditory stimuli. Participants had little activation of the PAR pre-training and this ability was not improved through CRM training. These results are contrary to Markotjohn (2020; 2023) who found reflexive PAM activation during auditory attention tasks. This may indicate that the tones in noise tasks of the facilitation phase did not elicit comparable auditory attention to tasks involving more naturalistic hearing (i.e speech in noise).

A significant training effect was seen in intentional unilateral PAM activation ipsilateral to the direction of interest. Interestingly, this effect was seen in the non-naturalistic hearing task (tones in noise) but not seen in the naturalistic hearing task of the skill acquisition phase (speech in noise). It is hypothesized that this was due to (1) effective skill acquisition of non-naturalistic auricular control, and (2) greater baseline acuity for auricular control in naturalistic hearing tasks.

Regarding research question #1, this study provides evidence for active and intentional PAM activation as a learned skill capable of use *with* directional auditory attention, but that spatial auditory attention alone does not elicit auricular orientation to stimuli at high signal-to-noise ratios.

4.2 Research Question #2

Can an auditory attention training regime increase the reliability and/or magnitude of intentional PAM activation?

At the group level, significant improvements in both the magnitude of PAM contraction and the reliability of correct lateralized contraction were increased following an auditory auricular training paradigm. Not all participants were able to achieve this degree of trained response, however 70% of participants garnered some degree of significant auricular control post-training. At the level of the ear, only 55% achieved significant training effects, however this is still consistent with previous auricular training regimes (Chanthaphun et al., 2019).

Of the 3 participants who did not achieve significant improvement, 2 self-reported as previous ‘ear wigglers’ and 1 as a ‘non-wiggler’. Four of the 5 self-reported ‘non-wigglers’ and 3 out of 5 ‘ear wigglers’ achieved at least a unilateral training effect for PAM activation. There does not appear to be an effect of previous self-identified auricular control on one’s capacity to improve the magnitude and reliability of PAM contraction through auditory attention tasks. This is consistent with results from Schmalfuß et al. (2016) indicating that control of auricular myogenically driven vehicles was learnable by those with and without previous ability.

A contrary training effect was seen in participant 007's right PAM wherein post-training magnitude was significantly reduced. 007 showed strongly significant left PAM bias (Table 3.5) despite displaying bilateral improvement in PAM magnitude across CRM training (Figure 3.2). The relatively greater increase in left PAM magnitude as compared to right could have had two potential impacts on intentional facilitative PAM activation: (1) magnitude differential between right and left ears created a false negative bias during preprocessing; (2) the greater improved magnitude of left PAM contraction biologically biased the participant to activate that muscle group despite the target side. Since right PAM magnitude increased across CRM training, this author hypothesizes the former to account for this result.

Auditory auricular myogenic training using the paradigm described in this project appears to be an effective method to increase both the reliability and magnitude of intentional PAM contraction especially in a non-natural listening task. In a more natural listening task, improvement in PAM magnitude tended to be present but not at a level deemed significant for most participants. Correct lateralization was achieved through CRM training for all but participants 002 and 004 indicating that even without significant training effect on magnitude and despite baseline auricular favouring, correct unilateral activation is highly trainable.

4.3 Research Question #3

Can one reliably deduce auditory directionality and selectively activate auricular muscles in the direction of interest?

All participants except for 002 and 004 showed trainable lateralization of PAM activation to auditory stimuli. This provides further evidence for an intact neural circuitry for intentional and unilateral auricular myogenic control in humans alongside Schmalfuß et al. (2016), Chanthaphun et al. (2019), and Markotjohn (2020, 2023). The present study was the first to harness this circuitry through auditory training.

Of the 2 participants who were unable to achieve correct PAM lateralization, neither showed significant improvements in intentional or reflexive PAM activation overall. This indicates that, when the ability to train manual PAM manipulation is present, lateralization is also present as seen at a rate of 80% in this study.

4.4 Research Question #4

Does auditory training increase reflexive PAM activation to directional auditory stimuli?

Intentional PAM activation was seen in both the more naturalistic CRM training task and the less naturalistic tones-in-noise training task. The result of intentional PAM manipulation increasing significantly only in the non-naturalistic setting was unexpected. Strauss et al. (2020) found greater intentional and reflexive auriculomotor activity in tasks requiring auditory attention. It is hypothesized that sustained goal-oriented auditory attention increased baseline PAM magnitude in the naturalistic listening task thereby narrowing the range of improvement magnitude. This study found little-to-no reflexive PAM activity, contrary to Strauss et al. (2020) who assessed reflexive activity to startling auditory stimuli. The present study used a non-startling listening task with non-naturalistic stimuli at a high (+15 dB) signal-to-noise ratio. Apart from startle-based paradigms, reflexive engagement of the PAM may require more challenging listening tasks. It is further hypothesized that, in this non-naturalistic setting, baseline PAM activity is low allowing for contraction velocities comparable to those during CRM training to falsely appear as more significant.

While this study did not find improvement in reflexive PAM activation to auditory stimuli, it is unclear as to the role of naturalistic speech tasks or non-naturalistic tones-in-noise tasks, and of attention-grabbing (i.e startling) rather than attention-sustaining stimuli in reflexive PAM activation. In the present study, it cannot be suggested that auditory auricular myogenic training influences reflexive PAM activity, at least for non-naturalistic sounds in non-challenging (high SNR) listening tasks.

4.5 Implications

This study provides foundational evidence for auditory training of the PAM. Previous studies on auriculomotor training have focused exclusively on visual and motor tasks. The present study provides a simple and highly adaptable speech-in-noise training paradigm which was shown to effectively improve PAM contraction magnitude and correct lateralization to some degree in the majority of participants. This indicates that auriculomotor activity is highly trainable through an auditory-only modality despite previous (in)ability or auricular favouring.

All data stored in this study were pre-processed as baseline-corrected during data collection. While this allowed for detailed tracking of lateralized changes in sEMG responses over training, it did not account for individual baseline variation across participant or across training phase tasks. Any real-world application of PAM-activated devices would require modelling baseline sEMG activity (including head and neck movement) in order to detect specific engagement of the PAM, however this was not a problem we attempted to solve in this study.

The present study did not assess non-naturalistic (facilitation phase) hearing tasks during CRM training. It is therefore impossible to determine from this study at what point significant improvement in intentional PAM activation was achieved. We cannot, therefore, state with certainty if 5 training sessions was superfluous or if continued training would have predicted further improved contraction magnitude. This study provides evidence that 5 auditory training sessions is, however, sufficient to achieve manual lateralized control of the PAM in a majority of subjects.

A majority of participants showed a reliable trained ability to produce sEMG responses at an SNR above both their baseline activity and their opposite ear. This provides evidence for the feasibility of trained lateralized auricular control for goal-oriented listening. Future studies comparing such responses to baseline activity within participants would be required to assess the feasibility of translating sEMG activity to wearable technologies, however this study found a cut-off SNR of 1.20 to be sufficient to achieve reliable responses with minimal false positives.

CHAPTER 5 CONCLUSIONS

This project explored the use of sEMG to assess reflexive and intentional activity of the PAM preceding and following an auditory training regime. Of 10 participants, 8 were able to achieve correct lateralization of responses and 7 were able to achieve some degree of significant improvement in intentional magnitude of contraction through the designed paradigm. Reflexive PAM activation was not improved through training, however the present study did not assess the PAMR as a startle response and used stimuli at a non-challenging +15 dB SNR. Intentional manipulation of the PAM appears to be highly trainable and offers a new opportunity for sEMG operated devices. Technological development of hearing aids which can harness the electrical changes of the skin due to PAM contraction would allow hands-free manipulation of device features and/or microphone beamform directionality. In particular, this technology offers potential for manual directionality for speech in competing speech, where traditional hearing aids struggle to isolate the desired speech stimulus rather than simply the most audible. Additionally, this training offers opportunities for other types of devices including supporting additional training regimes for myoelectric auricular controlled vehicles for those with mobility issues and a hands-free manipulation tool for augmentative and alternative communication devices. Myographic auricular training may not be an option for all, but a majority of people are able to achieve some degree of functionality opening the option to assign this vestigial neural pathway to more complex and practical functions.

BIBLIOGRAPHY

Algazi, V., Duda, R., Thompson, D., & Avendano, C. (2001). The CIPIC HRTF database. In: *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics*, p. 99–102.

Andreopoulou, A., & Roginska, A. (2011). Documentation for the MARL-NYU file format description of the HRIR repository. *Music and Audio Research Laboratory, New York University*. Retrieved from: https://steinhardt.nyu.edu/marl/research/resources/head-related-impulse-responses-repository-0.

Bates, D., Mächler, M., Bolker, B.M., & Walker, S.C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1-48. doi: 10.18637/jss.v067.i01.

Begak, O. (2024). *Female head vector illustration in front, back, top, side view* [Image]. Olga Begak Art. https://stock.adobe.com/ca/contributor/209612813/olga-begak-art?asset_id=436901678.

Beretta-Piccoli, M., Cescon, C., Barbero, M., & D'Antona, G. (2019). Reliability of surface electromyography in estimating muscle fibre conduction velocity: a systematic review. *Journal of Electromyography and Kinesiology, 48*, 53-68. doi: 10.1016/j.jelekin.2019.06.005.

Chanthaphun, S., Heck, S.L., Winstein, C.J., & Baker, L. (2019). Development of a training paradigm for voluntary control of peri-auricular muscles: a feasibility study. *Journal of NeuroEngineering and Rehabilitation, 16*(75), 1-11. doi: 10.1186/s12984-019-0540-x.

Dai, L., Best, V., & Shinn-Cunningham, B.G. (2018). Sensorineural hearing loss degrades behavioral and physiological measures of human spatial selective auditory attention. *Proceedings of the National Academy of Sciences of the United States of America, 115*(14), E3286-E3295. doi: 10.1073/pnas.1721226115.

Farina, D., & Merletti, R. (2004a). Estimation of average muscle fibre conduction velocity from two-dimensional surface EMG recordings. *Journal of Neuroscience Methods, 134*, 199-208. doi: 10.1016/j.jneumeth.2003.12.002.

Farina, D., & Merletti, R. (2004b). Methods for estimating muscle fibre conduction velocity from surface electromyographic signals. *Medical & Biological Engineering & Computing, 42*(4), 432-445. doi: 10.1007/BF02350984.

Fox, J.E., Peyton, M.B., & Ragi, E. (1989). Lability of the postauricular and inion microreflexes, studied in the normal human subject. *Electroencephalography and Clinical Neuroscience, 72*(1), 48-58. doi: 10.1016/0013-4694(89)90030-8.

Hackley, S.A. (2015). Evidence for a vestigial pinna-orienting system in humans. *Psychphysiology, 52*(10), 1263-1270. doi: 10.1111/psyp.12501.

Hackley, S.A., Ren, X., Underwood, A., & Valle-Inclán, F. (2017). Prepulse inhibition and facilitation of the postauricular reflex, a vestigial remnant of pinna startle. *Psychphysiology, 54*(4), 566-577. doi: 10.1111/psyp.12819.

Kassambara, A. (2023). *rstatix: Pipe-friendly framework for basic statistical tests*. R package v. 0.7.2. URL: https://rpkgs.datanovia.com/rstatix/.

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., & Jensen, S.P. (2022). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software, 82*(13), 1-26. doi: 10.18637/jss.v082.i13.

Markotjohn, M.E. (2020). *Vestigial orienting in speech perception* [Unpublished Honour's thesis]. Dalhousie University.

Markotjohn, M.E. (2023). *Post-auricular orientation of auditory attention in sound field versus virtual sound space* [Unpublished Master's thesis]. Dalhousie University.

Neher, T., Behrens, T., Carlile, S., Jin, C., Kragelund, L., Petersen, A.S., & van Schaik, A. (2009). Benefits from spatial segregation of multiple talkers in bilateral hearing-aid users: effects of hearing loss, age, cognition. *International Journal of Audiology, 48*(11), 758-774. doi: 10.3109/14992020903079332.

Petersen, E.B., Wöstmann, M., Obleser, J., & Lunner, T. (2017). Neural tracking of attended versus ignored speech is differentially affected by hearing loss. *Journal of Neurophysiology, 117*, 18-27. doi: 10.1152/jn.00527.2016.

Populin, L.C., & Yin, T.C.T. (1998). Pinna movements of the cat during sound localization. *The Journal of Neuroscience, 18*(11), 4233-4232. doi: 10.1523/JNEUROSCI.18-11-04233/1998.

R Core Team. (2022). R: A language and environment for statistical computing. The R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/

RStudio Team. (2024). RStudio: Integrated Development for R. RStudio, PBC, Boston, MA. URL: http://www.rstudio.com/.

Schmalfuß, L., Rupp, R., Tuga, M.R., Kogut, A., Hewitt, M., Meincke, J., Klinker, F., Duttenhoefer, W., Eck, U., Mikut, R., Reischl, M., & Liebetanz, D. (2016). Steer by ear: myoelectric auricular control of power wheelchairs for individuals with spinal cord injury. *Restorative Neurology and Neuroscience, 34*(1), 79-95. doi: 10.3233/RNN-150579.

Strauss, D.J., Corona-Strauss, F.I., Schroeer, A., Flotho, P., Hannemann, R., & Hackley, S.A. (2020). Vestigial auriculomotor activity indicates the direction of auditory attention in humans. *Neuroscience, 9*(e54536), 1-18. doi: 10.7554/eLife.54536.

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer-Verlag New York. ISBN: 978-3-319-24277-4; URL: https://ggplot2.tidyverse.org.

Yoshie, N., & Okudaira, T. (1969). Myogenic evoked potential responses to clicks in man. *Acta Oto-Laryngologica, 67*(sup252), 89-103. doi: 10/3109/00016486909120515.

APPENDIX A CODING USED FOR STATISTICAL ANALYSES

A.1 Coordinate Response Measure Training

CRM data:

```
crmraw <- read.csv("C:/Users/simon/Documents/MSc Aud/Thesis/crmdatfinal
.csv", header = TRUE, sep = ",", fill = TRUE)
head(crmraw)

##   participant session block cue correct    pam
## 1           1       1     1   l       y 0.9715
## 2           1       2     1   l       y 1.0198
## 3           1       3     1   l       y 2.1528
## 4           1       4     1   l       y 1.3280
## 5           1       5     1   l       y 2.0065
## 6           2       1     1   l       y 2.8033
```

Reformat data:

```
crmraw$participant <- as.factor(crmraw$participant)
crmraw$session <- as.factor(crmraw$session)
crmraw$block <- as.factor(crmraw$block)
crmraw$cue <- as.factor(crmraw$cue)
crmraw$correct <- as.factor (crmraw$correct)
```

Remove participant 8:

```
crm <- crmraw %>%
filter(participant != '8')
```

Shapiro and QQ plot show normal distribution

```
crm %>%
group_by(participant, session, correct) %>%
shapiro_test(pam)

ggqqplot(crm, "pam", ggtheme = theme_bw()) +
  facet_grid(participant ~ session, labeller = "label_both")
```

Summary stats:

```
crm %>%
group_by(participant, session, correct) %>%
get_summary_stats(pam, type = "mean_sd")
```

Group data:

```
oneway <- aov(pam ~ session, data = crm)
summary(oneway)
```

Linear effect model:

```
crm.aov <- lmer(pam ~ session + cue + (cue*correct) + (session*correct)
+ (1|participant), data = crm)
anova(crm.aov)
```

Significant differences in session, cue, and correct activation across all participants during training:

```
pwcrmsession <- crm %>%
group_by(participant, cue) %>%
pairwise_t_test (pam ~ session, paired = TRUE,
p.adjust.method = "bonferroni")

pwcrmcue <- crm %>%
group_by(participant) %>%
pairwise_t_test (pam ~ cue, paired = TRUE,
p.adjust.method = "bonferroni")

pwcrmcorrect <- crm %>%
group_by(participant) %>%
pairwise_t_test (pam ~ correct, paired = TRUE,
p.adjust.method = "bonferroni")
```

A.2 Reflexive PAM Training

```
refraw <- read.csv("C:/Users/simon/Documents/MSc Aud/Thesis/refdatfinal
.csv", header = TRUE, sep = ",", fill = TRUE)
head(refraw)

##   participant session block cue   pam pam.incorrect pam.corrected
## 1           1       1     1   l 0.892         0.855         0.037
## 2           1       1     2   l 0.978         0.987        -0.009
## 3           1       1     3   l 1.001         0.985         0.016
## 4           1       1     4   l 1.003         0.999         0.004
## 5           1       1     5   l 0.987         1.016        -0.029
## 6           1       1     6   l 0.915         0.993        -0.078

refraw$participant <- as.factor(refraw$participant)
refraw$session <- as.factor(refraw$session)
refraw$block <- as.factor(refraw$block)
refraw$cue <- as.factor(refraw$cue)
```

All participants are normally distributed when comparing Shapiro test with qqplots:

```
refraw %>%
group_by(participant) %>%
shapiro_test(pam.corrected)

ggqqplot(refraw, "pam.corrected", ggtheme = theme_bw()) +
  facet_grid(participant ~ session, labeller = "label_both")
```

Summary stats:

```
refraw %>%
group_by(participant, session) %>%
get_summary_stats(pam.corrected, type = "mean_sd")
```

Group data:

```
oneway <- aov(pam.corrected ~ session, data = refraw)
summary(oneway)
```

Linear effect model:

```
refraw.aov <- lmer(pam.corrected ~ session + cue + (1|participant), dat
a = refraw)
anova(refraw.aov)
```

Significant difference between L/R bias (i.e. pre-training vs. post-training). Pairwise t-tests revealed significant only for participants 4 and 11:

```
pwref <- refraw %>%
group_by(participant) %>%
pairwise_t_test (pam.corrected ~ cue, paired = TRUE,
p.adjust.method = "bonferroni")
```

A.3 Intentional PAM Training

```
intraw <- read.csv("C:/Users/simon/Documents/MSc Aud/Thesis/intdatall.c
sv", header = TRUE, sep = ",", fill = TRUE)
head(intraw)

##   participant session block cue   pam pam.incorrect pam.corrected
## 1           1       1     1   l 0.963         0.933         0.030
## 2           1       1     2   l 0.948         0.902         0.046
## 3           1       1     3   l 0.956         0.912         0.044
## 4           1       1     4   l 0.997         0.960         0.037
## 5           1       1     5   l 0.937         0.957        -0.020
## 6           1       1     6   l 0.997         1.003        -0.006

intraw$participant <- as.factor(intraw$participant)
intraw$session <- as.factor(intraw$session)
intraw$block <- as.factor (intraw$block)
intraw$cue <- as.factor(intraw$cue)
```

All participants are normally distributed when comparing Shapiro test with qqplots:

```
intraw %>%
group_by(participant) %>%
shapiro_test(pam.corrected)

ggqqplot(intraw, "pam.corrected", ggtheme = theme_bw()) +
  facet_grid(participant ~ session, labeller = "label_both")
```

Summary stats:

```
intraw %>%
group_by(participant, session) %>%
get_summary_stats(pam.corrected, type = "mean_sd")
```

Group data:

```
oneway <- aov(pam.corrected ~ session, data = intraw)
summary(oneway)

intstat <- intraw %>%
  t_test(pam.corrected~session) %>%
  adjust_pvalue(method = "bonferroni") %>%
  add_significance() %>%
  add_xy_position(x = "session")
intstat
```

Linear effect model:

```
intraw.aov <- lmer(pam.corrected ~ session + cue + (1|participant), dat
a = intraw)
anova(intraw.aov)
```

Significant difference between session 1 and 2 (i.e. pre-training vs. post-training) and in L/R activation bias. Pairwise t-tests revealed session significance for participants 1, 4, 5, 6, 8, 9, 10, 11:

```
pwint <- intraw %>%
group_by(participant, cue) %>%
pairwise_t_test (pam.corrected ~ session, paired = TRUE,
p.adjust.method = "bonferroni")

pwintcue <- intraw %>%
group_by(participant, session) %>%
pairwise_t_test (pam.corrected ~ cue, paired = TRUE,
p.adjust.method = "bonferroni")
```