Impacts of auditory-tactile training on auditory perceptual learning

by

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Abstract

Perceptual experiences tend to be multisensory ones, yet multisensory perceptual learning is not as often studied as learning in the individual senses (i.e. vision, audition, **or** somatosensory). These studies looked at auditory-tactile training in comparison to unimodal auditory-only training on auditory perceptual tasks. A series of experiments were completed in which participants were trained with unimodal auditory-only or synchronous, multimodal auditory-tactile sounds in temporal discrimination, perceptual categorization, and perceptual thresholding tasks. Some experiments tested generalization to auditory-only detection tasks or used auditory-only testing of the same task used during multisensory training. Sensitivity (*d'*) and thresholds were measured and compared across training conditions, and over time. These experiments were expected to replicate multisensory learning enhancements in perceptual sensitivity, but extend this literature to the somatosensory domain and its relationship with audition. Overall, these studies found an increase in learning over time, so these experimental paradigms do work for training purposes. However, there was only one occasion in which auditory-tactile learning occurred at an accelerated rate over time compared to the auditory-only training, and we believe this occurred due to an initial disadvantage of auditory-tactile presentation on perception. We discuss the possible mechanisms of multisensory learning benefits, and why they may not have been found in these studies. This research will be used to establish a behavioral paradigm for future EEG research to study auditory evoked potentials (AEPs) and the plasticity associated with multisensory training effects. In the applied realm, this research may inform optimal perceptual training methods that are relevant to real-world perception issues (e.g., reactions to familiar sounded alarms; rehabilitation in auditory processing disorders).

Keywords: perceptual learning; plasticity; crossmodal; audiotactile; training

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Acknowledgements

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Chapter 1 - Introduction

The joke "why did the chicken cross the road" has been told many times. The most popular punchline is "to get to the other side". While this answer may appear straight forward, the simple action to get across the road is a bit more complex. As a child, you may have been taught to check the road before crossing it. The simple act of crossing the road must be preceded by visually checking both to the left and right of the viewer's position, listening for any vehicles that might be coming (which is especially important if crossing near a bend or curve in the road), and feeling if any vibrations of an engine running, horn honking, or tires hitting pavement are nearby. This experience is a multisensory one- using integration of information across modalities to make a decision about crossing the road.

While life experiences typically occur in this multisensory manner, it tends to be that sensory modalities and their perceptions are studied individually. This is especially true in regard to the study of how experience impacts perception (i.e., perceptual learning). Even though our real-world experiences are multi-modal, perceptual learning studies have heavily focused on unimodal learning experiences (for review, see Goldstone, 1998; Ahissar et al., 2009; Maniglia & Seitz, 2018). The purpose of this study was to compare perceptual learning for sound under unimodal and multimodal training experiences. The data more adequately reflect real world experience than unimodal studies, provide a characterization of multimodal perceptual learning for theory development, and potentially reveal training procedures that can accelerate or deter inhibition of the learning process.

Multi-modal perceptual learning

Multimodal training occurs when stimuli from different sensory domains are presented near simultaneously in a perceptual learning task. Typical studies that use this paradigm compare performance after multimodal training or unimodal training for a unimodally tested task. For example, Liu et al. (2011) and Liu (2012) compared unimodal sound-only training to multimodal congruent audiovisual training for two auditory perceptual tasks involving change detection and discrimination. The sounds used were sounds either rising or falling in pitch, and congruent visual stimuli were disks on a screen that either grew in size (referred to as ‘looming disks’) or shrunk in size (referred to as ‘receding disks’). They found that sensitivity (measured by *d*’) in the auditory detection and discrimination tasks significantly improved for the multimodal congruent condition from pre-test to post-test. There were no significant changes in sensitivity from pre- to post-tests for the unimodal training group. Other advantages of multimodal perceptual learning have included reduced reaction times (RTs) and higher accuracy in performance than typical unimodal training paradigms (Göschl et al., 2015; see *Figure 1* for a diagram of some observed multimodal benefits).

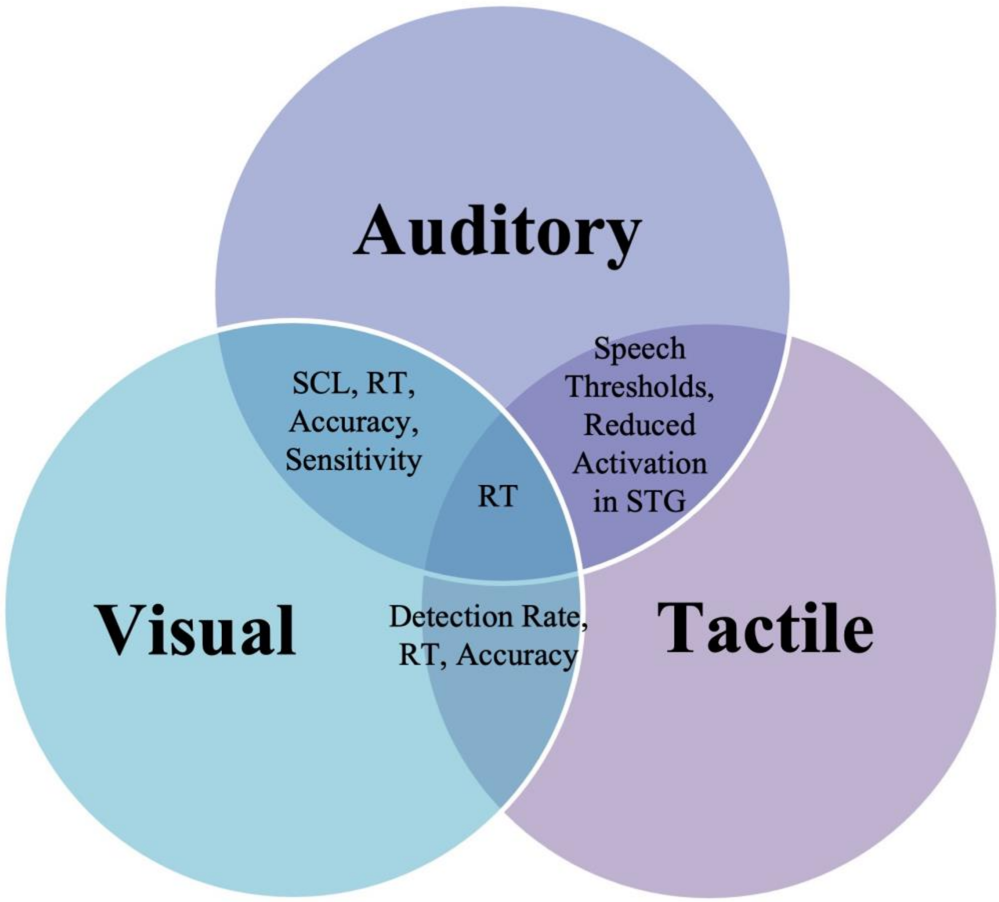

Figure 1. *Benefits of Multimodal Training & the Combining Sensory Modalities.*
Auditory-Visual benefits have included: decreased subjective cognitive load (SCL; Gerven et al., 2006), faster reaction time (RT; Molholm et al., 2002), improved accuracy (Chen & Spence, 2010), and increased sensitivity (Lui et al., 2011; 2012). Auditory-electrotactile benefits have included reduced speech thresholds in comparison to auditory-only (Huang et al.,2017). Auditory-tactile (haptic/active) found reduced brain activity in the right superior temporal gyrus (STG; Chen et al., 2012). Visual-tactile have found benefits of detection rate compared to visual-only (Göschl et al., 2015), faster reaction times (Forster et al., 2002), and increased accuracy (Göschl et al., 2015).

Not only are these physical behavioral effects seen, but mental relief such as reduction of cognitive load were found from training in bimodal compared to unimodal conditions. In particular, Gerven et al. (2006) found that both younger and older adults' subjective cognitive load (SCL) was significantly reduced in a bimodal auditory-visual training condition compared to a unimodal visual-only condition. It has also been found that older adults take larger advantage of multisensory enhancement than younger adults; this larger advantage has been associated with older adults' declining perceptual and cognitive abilities. As age increases, perceptual sensitivity, the ability to inhibit distractions, and memory all decline (Miller, 1982; 1986).

Other related perceptual learning effects involve crossmodal transference. This occurs when training in one modality alone impacts perception in another modality. For instance, exposure to auditory rhythms can impact perception of rhythms presented visually (Grahn et al., 2011; also see Kim & James, 2010; King, 2009). This crossmodal transference effect has also been found in temporal discrimination tasks in which participants were trained in the tactile modality, but saw increases in performance to this task when presented in the auditory modality (Nagarajan et al., 1998); these same effects have also been found in fMRI data in which individuals whom had audio-tactile training had activation of the somatosensory cortex in a later test only involving auditory stimuli, as well as a significant reduction in reaction time compared to the unimodal trained group (Junker et al., 2021). This shows that multimodal training yields neural plasticity that allows stimulation in one modality to cause activation of representations for another modality.

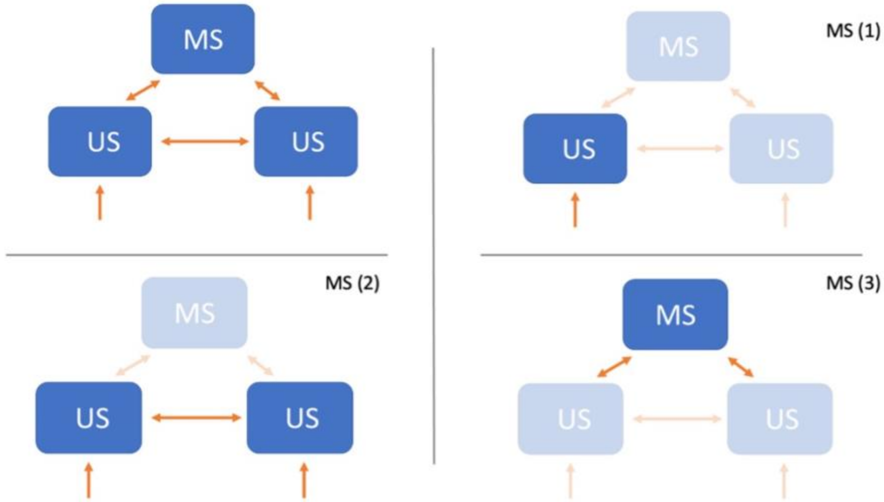

Figure 2. *Multisensory Learning Mechanisms.*
Depictions of different multisensory learning mechanisms via their changes in plasticity with multisensory (MS) and unisensory (US) representations and connections.

The finding that multimodal training impacts unisensory perception has been well demonstrated. However, the mechanisms that produce these effects are still debated. At least 3 possible explanations for multisensory learning effects exist. Figure 2 is adapted from Junker et al. (2021) to depict these different possibilities. Advantages could arise from plasticity in unisensory representations (MS1 in *Figure 2*; Lappe et al., 2008, 2011; Chen et al., 2012), plasticity in the connectivity between representations in different sensory systems (MS2 in *Figure 2*; Scholz et al., 2009; von Kriegstein & Giraud, 2006), and/or plasticity in multisensory representations (MS3 in *Figure 2*; Naumer et al., 2009; Paraskevopoulos et al., 2012; Junker et al., 2021). Another issue is whether multimodal training effects are actually due to some multimodal enhancement, or just due to a multitude of cues. One relevant finding is that the benefits of multisensory presentation have only been found when both unisensory representations of the multisensory stimulus are congruent to one another. It has repeatedly been found that incongruent multimodal training (Liu, 2012) or stimulus presentation in attentional cueing paradigms (Fu et al., 2021) lead to reduced performance and sensitivity and increased RT.

This suggests a dependence on integration across modalities. Nevertheless, in studies that do not compare multimodally integrated stimuli (e.g., stimuli concurrent in time) to non-integrated stimuli (stimuli occurring at separate times), a benefit of multiple encoding cues cannot be ruled out. For some studies, this has left some uncertainty as to whether results truly show a multimodal training enhancement effect.

Chapter 2 - Current Study

Little research has focused on the relationship between auditory and tactile modalities during learning. In particular, crossmodal training in these domains are sparse, especially regarding their temporal properties. Timing is an amodal property, so can be researched across modalities and likely also uses more information from multiple sensory systems (Chen & Zhou, 2014). Though a previous pilot study of mine showed auditory and tactile 75% thresholds for discriminating temporal intervals are not the same (see *Figure 3* below), they are relatively similar and have been found to be in similar psychological distance previously (Nagarajan et al., 1998). It is for these reasons that I chose to study multimodal perceptual learning in the auditory and tactile modalities.

These studies aimed to describe the relationship of multimodal auditory-tactile versus unimodal auditory-only training on auditory-only discrimination tasks. Impacts of training on performance in the auditory modality alone was examined because pilot studies revealed a difference in tactile and auditory thresholds that would make it difficult to examine impacts of training on both modalities. Further, the EEG features associated with auditory learning are better worked out in the literature, making it easier to extend this work to future EEG studies.

Low-level integration features (e.g. synchronous timing, spatial congruency) were used to help with integration across tactile and auditory modalities. In experiment 1, participants completed pre-test, training, and post-test sessions (all with feedback) across 1 day, where they learned to discriminate between stimuli based on temporal properties. Half of the participants were trained in the auditory-only group, and the other half in the audio-tactile group. Latter experiments all used within-subject training/thresholding to help account for individual differences in tactile voltage levels, sensitivity, and multisensory auditory-tactile thresholds.

Experiment 2 explored effects of auditory-tactile training on an auditory categorization task, and generalization of this training to an auditory detection task. Experiment 3 used another temporal discrimination task to find thresholds for auditory and auditory-tactile stimuli. My primary hypotheses were that:

(1) Perceptual learning will occur in that sensitivity or thresholds will improve through training,

(2) Joint auditory-tactile training (as compared to unimodal auditory training) will yield stronger changes in auditory perception, and

(3) Auditory-tactile stimuli will have smaller thresholds compared to auditory-only.

Chapter 3 - Experiment 1: Temporal Gap Judgement

Experiment 1 was an initial test of whether joint auditory-tactile stimulation during training impacts perceptual learning for sound. It was designed to reveal an effect of auditory-tactile enhancement (if it exists), in a comparison that previous multimodal perceptual research suggests that such an effect should be strongest. That is, at zero delay between auditory and tactile stimulation. If there is an impact of coincident tactile stimulation on the learning of sound, we should observe differences in pre- to post-test perceptual improvements when comparing unimodal (auditory only) and multimodal (auditory and tactile) trained groups.

Methods

Participants. Students were undergraduates at Kansas State University (Manhattan, KS) and consisted of ages 18 to 22 (M_{Age}=19). Participants were encouraged through Psychology courses at Kansas State University to participate in on-campus research. Participants signed up through an online system called "Sona Systems" (Sona-Systems [Apparatus and Software], 2019) and received research credit for their classes for participating in this study. Prior to participating, participants gave their written informed consent. All procedures were approved by the Kansas State University Institutional Review Board (IRB). A total of 40 participants were recruited, 20 for each training group. Participants were randomly assigned to be trained either in a unimodal auditory condition or the multimodal auditory-tactile condition (see below for training details). All participants in the study reported to have normal hearing, and performed above chance level; so, no participants met our exclusion criteria (non-normal hearing and/or below-chance performance).

Equipment. All stimuli were presented over two Mackie CR3-X speakers (Mackie, Bothwell, Washington) (one on the left of the experimental screen and one on the right) connected to an RME UC audio interface (RME Audio, Germany). Listeners sat in a WhisperRoom (WhisperRoom, Knoxville, TN) double walled sound attenuating booth throughout the study. Subject interaction with experimental GUIs was accomplished with an XBOX video game controller operating as a computer mouse (Microsoft, Redmond, WA). Tactile stimulation was delivered through a DS2A Isolated Voltage Stimulator (Digitimer Ltd, Hertfordshire, England) with voltage set for each participant at a level just below their individualized identification of a level that is “annoying, but not painful” (see below for tactile calibration). All experimental programs were executed in MATLAB (Mathworks, Natick, MA).

Stimuli. Stimuli consisted of 2 noise bursts and/or electrotactile bursts of the same duration (10ms per burst). These were separated by an interval of 90ms (*fast*) or 130ms (*slow*). These values were determined from data from a preliminary experiment in which participants' ~75% thresholds for "slow" versus "fast" discrimination was determined for tactile and auditory stimulation separately. A gap of ~40ms was determined to be the appropriate difference needed to distinguish between “fast” and “slow” for the auditory modality (see *Figure 3*).

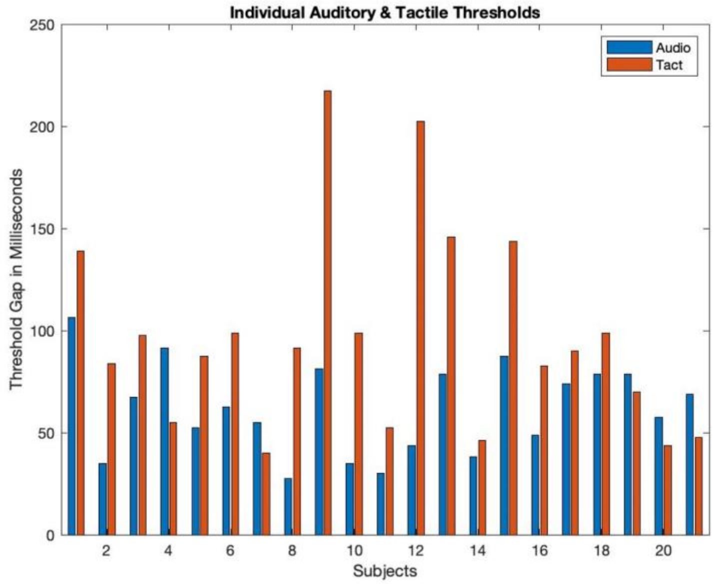

Figure 3. *Auditory & Tactile Difference Gap Thresholds from Pilot 1.*
(*n* = 21) Participants completed 240 trials of each modality (auditory-only and tactile-only) across a total of 6 blocks (3 blocks per modality presented in random order). The "Fast" ISI gap was fixed at a constant of 90ms, while the "Slow" ISI gap started at 240ms and a single-interval adjustment matrix (SIAM) procedure was used to determine each of the next trials' slow ISI gap based on the participant's response from the previous trial. Median gap thresholds needed to distinguish between "slow" and "fast" were ~60ms for auditory and ~90ms for tactile, similar to findings in previous research (Nagarajan et. al, 1998).

Tactile Calibration. Stimulation voltage for each participant was determined prior to the experiment using a tactile calibration protocol (see *Appendix A*) that was based off of protocols used in previous studies (Kaczmarek et. al, 1994; Grillon et. al, 2004; Bobich et. al, 2007; D'Alonzo et. al, 2014; Nelson et. al, 2015; Huang et. al, 2017; Fletcher, 2021). Each participant's threshold, annoyance level, and actual level voltage from a single electrotactile pulse was recorded and stored with their participant ID number. The "threshold" level is the first voltage level (moving upward from 0V) that the participant reports as "feeling something". The annoying level was recorded when the participant reported the stimulation as "annoying, but not painful". The actual voltage for the experiment was then set to ~2V less than the "annoying" level. The DS2A Isolated Voltage Stimulator also has a safety feature in which the voltage cannot exceed 99V, with current not exceeding 50 mA. Range of participants' voltage used in included: 20V- 72V (*M* = 42V; *Median* = 38V).

Testing. Testing used a 1-interval- 2 Alternative Forced-Choice Task (1i-2afc). Participants were asked to respond if a stimulus was "Fast or Slow?". The experimental GUI is shown in Figure 4. Participants were tested only on the unimodal auditory condition. Prior to and after training, participants completed the unimodal auditory test (unimodal auditory pre and post-tests). Feedback (i.e. 'Correct' or 'Wrong') was provided after each trial so as to test perceptual discrimination and not just arbitrary Fast or Slow category response learning. There were 10 blocks per test, with 20 trials in each block (a total of 200 trials per test).

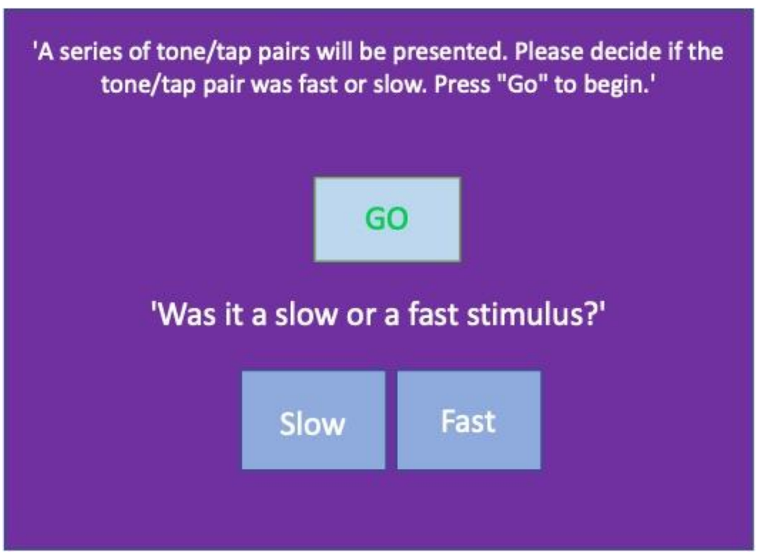

Figure 4. *1/2i-2AFC Task.*
Task is denoted as 1/2i-2AFC in title as in some cases the stimulus burst pairs may be presented unimodally (auditory-only; AO) or bimodally (auditory-tactile; AT).

Training. For training, participants were randomly assigned to either the unimodal auditory (AO) or the multimodal auditory-tactile (AT) training groups. Participants used the same task as testing. The key difference between training conditions were that the unimodal condition only had auditory stimuli, while the multimodal condition had auditory and tactile stimuli presented concurrently. There were 20 blocks of training with 20 trials in each block (a total of 400 trials in training). Figure 5 shows the order of procedures for Experiment 1.

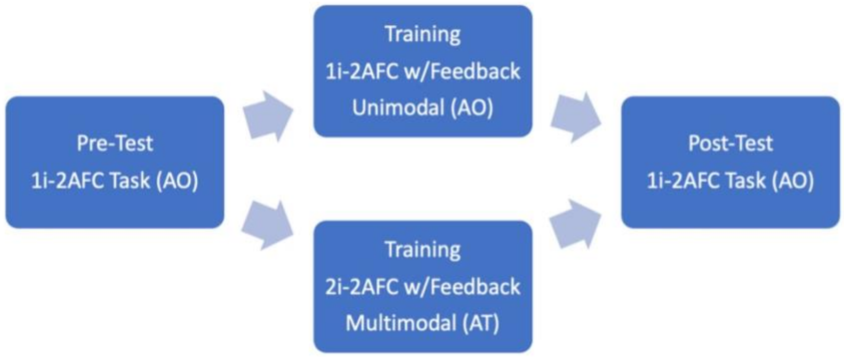

Figure 5. *Experiment 1 Procedure.*
Pre-Test, Training, and Post-Test all occur in one day. Training uses the same task as testing, but provides feedback and is manipulated to be between-subjects, where half are trained in the auditory-only (AO) condition and half are trained in the multisensory auditory-tactile (AT) condition.

Statistics. Data was analyzed in a signal detection theory (SDT) format using *d’* (see *Figure 6*) where:

$$d' = z(\text{hit}) - z(\text{fa}).$$

Each participant’s *d’* was calculated for both the pre-test and the post-test using a multilevel logistic regression with a Probit link function (Wright et. al, 2009).

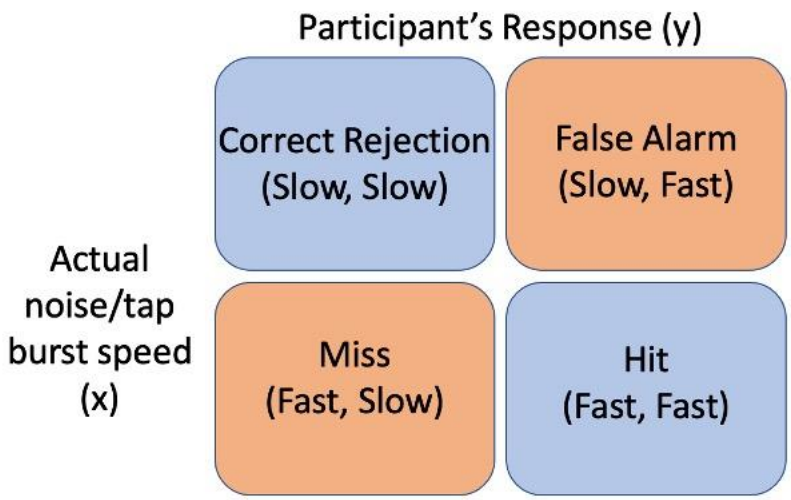

Figure 6. *SDT Layout of Data.*
The matrix above is in a 2x2 (x, y) contingency table where x = 'Actual noise/tap burst speed' (or the rows), and y = 'Participant's response' (or the columns). Participant's response is referred to as 'Said Fast', and actual noise/tap burst speed is referred to as 'Was Fast' in latter descriptions.

By using a multilevel logistic regression, it was possible to incorporate each trial's data without averaging or having to perform *d'* corrections prior to a statistical analysis. The participant's response (Said Fast) was predicted using the identity of the noise/burst speed presented (Was Fast), Test time (2 levels: Pre & Post) , Training Group (2 groups: Unimodal AO and Multimodal AT), and their interactions. Test and Training Group were both effect coded so that Pre-Test and Unimodal Auditory-Only training were the baseline values. The Was Fast predictor was recoded so that fast noise/burst were equal to +0.5 and slow noise/burst were equal to -0.5. This allows for the intercept to be interpreted as negative bias (-*c*), the Was Fast effect as the average *d'* across all conditions, and any Was Fast interactions as changes in *d'* due to an effect. All possible random effect (RE) structures were run, and the model with the lowest akaike information criterion (*AIC*) was reported. For this analysis, the RE structure consisted only of 'Subject' or the intercept-slope (*AIC*= 13, 389).

We predicted that:

H1: Sensitivity (as measured by *d'*) would improve across blocks (i.e. learning)

H2: The rate of improvement will vary across training modality; Specifically that participants trained in the audio-tactile condition would have a greater improvement in sensitivity across blocks compared to audio-only.

Results

It was found that Was Fast was a significant predictor of Said Fast in the model (β = 1.19, SE=0.03, p <.001), meaning participants were sensitive to the stimulus categories of fast and slow, and understood the task. A significant interaction of Was Fast x Test was found, and showed that participants' performance improved across Test as predicted in hypothesis 1 (β = -0.08, SE = 0.03, *p* =.001; see *Figure 7* and *Appendix B: Table 1*). There was no effect of training Modality; though, participants that trained with the Auditory-Tactile stimuli were slightly more sensitive on average in detecting fast auditory stimuli compared to slow (see *Figure 7*). However, no Was Fast x Test x Training Group interaction was found as hypothesized. So, there was no difference in the rate of learning between training groups.

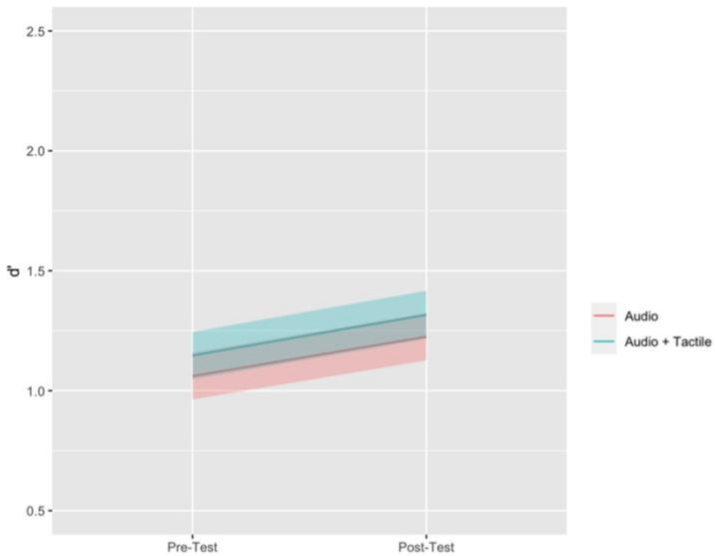

Figure 7. *Sensitivity (d') Changes Over Tests.*
Sensitivity (*d'*) changes in detecting 'Fast' stimuli from pre-test to post-test for auditory-only (AO) and auditory-tactile (AT) trained participants. The red and green lines represent the regression lines for the AO and AT conditions, and the shaded ribbons are 95% confidence intervals.

Discussion

We expected to find an advantage of multimodal over unimodal training for Experiment 1, which would mean that multimodal stimulation provided a better means of perceptual learning, concurrent with literature that has found crossmodal enhancement in RTs, accuracy, and sensitivity (Chen & Zhou, 2014; Chen & Spence, 2010; Gerven et al., 2006; Stein & Meredith, 1993; Liu, 2012; Liu et al (2011)). However, no multimodal enhancement effect was found. Perceptual learning did occur in this temporal gap judgement task, but was not found at differing rates dependent on training modality. In conclusion, this experiment did find that people can improve temporal discrimination in auditory perception through unimodal or multimodal training. This is helpful as there have been some research studies that have found that tactile time perception tends to be underestimated, while auditory and visual time perception tends to be overestimated (Di Lernia et al., 2018). That is, untrained temporal judgment can be poor initially, but may be able to be improved with training.

One possibility for why we may have not seen a benefit of the AT group for training has to do with the temporal judgment nature of the task. Bausenhart et al. (2014) used a similar 2i-2AFC task in which participants had to determine which gap stimulus (the 1st or 2nd) was "longer". They found that simultaneous auditory-visual stimuli (both congruent and incongruent) biased perceived duration in that "longer" intervals were judged to be ~10ms longer and "shorter" intervals were judged to be ~17ms shorter compared to visual-only presentations. They attribute this to the contingency of the information from different modalities, and how integration may be less effective between audition and vision due to differences in temporal processing in these sensory systems. For this reason, we switched to a task that used stimuli that weren't solely reliant on temporal properties so as to hopefully get stronger integration between auditory and somatosensory modalities.

Chapter 4 - Experiment 2A: Multisensory Categorization Training

The temporal properties of stimuli are a major factor in integration of multimodal stimuli (Holmes & Spence, 2006). As our task was a temporal judgement task and heavily relied on the temporal properties, we may not have seen a multimodal enhancement effect due to issues of integration between the auditory and tactile bursts that were presented during multimodal training. As such, Experiment 2 addresses this problem by using a perceptual categorization task that is not based on temporal features alone. Also, individual actual voltage level differed drastically between subjects in EXP 1, so EXP 2 accounted for this by having training modality as a within-subject factor in which subjects learned some stimulus patterns using auditory-only, and some patterns using auditory-tactile training. This was also expected to deal with the potential problem of preexisting differences that we observed in the pre-test of EXP 1.

Methods

Participants. A total of 30 college students were obtained at Kansas State University (Manhattan, KS). Students were undergraduates and consisted of ages 18 to 33 (M_{Age}= 20). Participant recruitment, sign-up, and consent process was the same as EXP 1. Participants that did not have normal hearing, or performed below chance (50% accuracy) were excluded from analyses. All participants in the study reported to have normal hearing, and performed above chance level; so, no participants met our exclusion criteria.

Equipment. All equipment use was the same from EXP 1.

Stimuli. Auditory stimuli consisted of randomly generated spectrotemporal sound patterns that were previously piloted, and found to have a $d' \approx 1$ with a task requiring the detection of a pattern among similar distractors. Each pattern was made up of 5 consecutively presented multitone complexes with frequencies of each tone complex selected randomly between 300Hz and 1200Hz. Each multitone complex in the pattern was 42ms in duration, making a pattern total length of 210ms (see *Figure 8* for example audio waveforms).

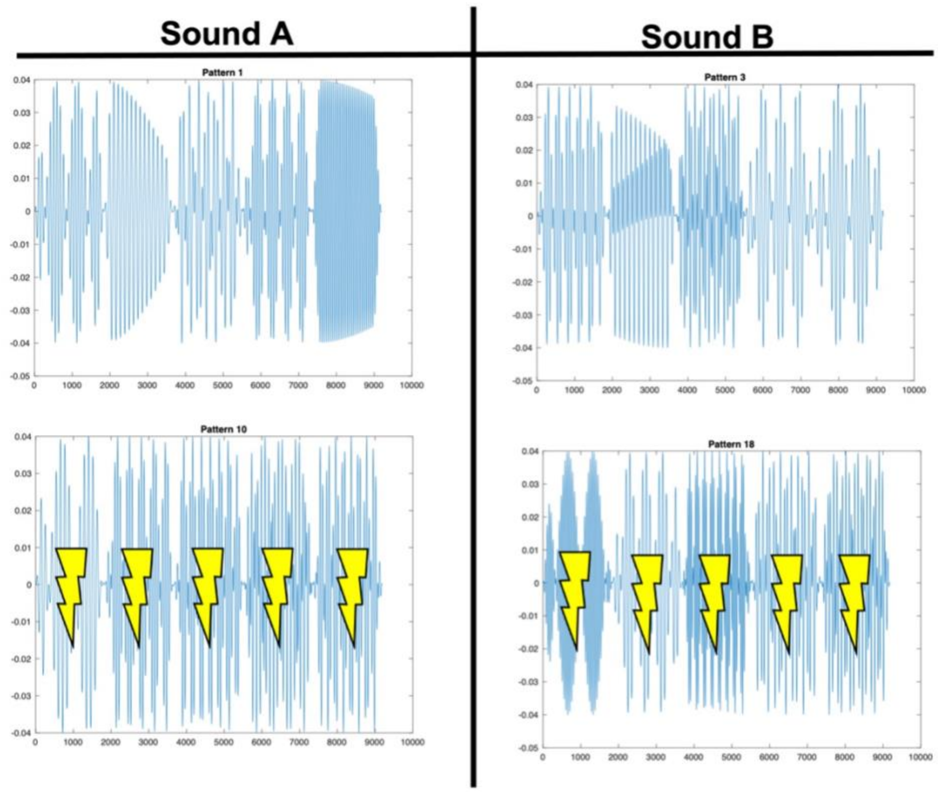

Figure 8. *Example of the Waveforms of the 4 Spectrotemporal Sound Patterns & Categorization Procedure.* Note that pattern names (i.e. "Pattern 10") were given to stimuli in the original 20 sound pattern pilot, and are just arbitrary labels. Lightning bolts represent the simultaneous electrotactile stimulation.

Tactile Calibration. Tactile calibration protocols and equipment are the same as EXP 1. Range of participants' voltage included: 13V- 83V (M = 30V; *Median* = 28V).

1i-2AFC Perceptual Categorization Task. Participants completed a 1-interval 2 alternative forced choice task in which the sound patterns would be presented through speakers (to the left & right of the computer monitor in front of the participant) either alone (auditory-only) or presented with a simultaneous electrotactile stimulation (auditory-tactile) to their right index finger that directly coincided with the sound patterns. Sound patterns were randomly assigned to “Sound A” and “Sound B” categories, with one pattern in each category being an auditory-only stimulus and one pattern being an auditory-tactile stimulus (see *Figure 8*). Participants had to learn through feedback of “Correct” or “Wrong” after each trial as to which patterns belonged to which category (‘Sound A’ or ‘Sound B’). Participants completed a total of 180 trials of this task (45 trials per sound pattern).

Statistics. Rather than aggregating our data prior to analyses, *d’* and negative bias (-*c*) can be calculated using a generalized linear mixed effect (GzLME) modeling approach. These have been found to reduce the likelihood of observing a Type 1 error by implementing both fixed effects (group-level) and random effects (individual level) and are the recommended data analysis technique for binomial choice data (Young, 2018). This particular GzLME model is a logistic regression with a Probit link function that calculates *d’* and negative bias (-*c*) using two columns recorded for every subject across every trial- stimulus present (i.e. “Was Fast”), and participant response (i.e. “Said Fast”). These columns are coded in as 0’s for “not present”, and 1’s for “present”.

In the analyses, Training Group (Auditory-Only vs. Auditory-Tactile) and Test were treated categorically and effect coded with Auditory-Only and Pre-Test as the contrasting conditions. A new parameter, Was Fast was included into the model to represent sensitivity. Was Fast was treated as a continuous variable and re-coded as -0.5 or +0 .5, for ‘not present’ or ‘present’ respectively. Including this additional parameter produces interpretable estimates which correspond to negative bias (-*c*; Intercept) and sensitivity (*d’*; Was Fast; Rader et al., 2021). The data were modeled using a full factorial model with Training Group, Was Fast, and Test as fixed effects to predict Said Fast. All possible random effect (RE) structures were run, and the model with the lowest *AIC* was reported. For this analysis, the RE structure consisted of Modality slope and Subject or the intercept-slope (*AIC*= 5,236).

We predicted that:

H1: Sensitivity (as measured by *d'*) would improve across blocks (i.e. learning)

H2: The rate of improvement will vary across modality; Specifically that audio-tactile would have a greater improvement in sensitivity across blocks compared to audio-only.

Results

Our results indicate that 'Was Sound B' was a significant predictor of 'Said Sound B' in the model (β = 1.71, SE=0.04, p <.001), meaning participants were sensitive to the stimulus categories, and understood the task. There was also a significant interaction between 'Was Sound B' and Block (β =0.13, SE = 0.02, p =<.001) showing that participants' performance improved across Block as predicted in hypothesis 1 (see *Figures 9-10* and *Appendix B: Table 2*). We also observed a significant interaction between 'Was Sound B' and Modality (β = -0.10, SE = 0.04, p = .017), showing a significant difference in sensitivity between Auditory-Only and Auditory-Tactile stimuli that was not previously observed. In particular, our Auditory-Tactile stimuli had greater *d'*- values (see *Figure 10*). However, we saw no significant Was Sound B x Block x Modality interaction; so there was no difference in the rate sensitivity improved across blocks between stimulus modality as hypothesized.

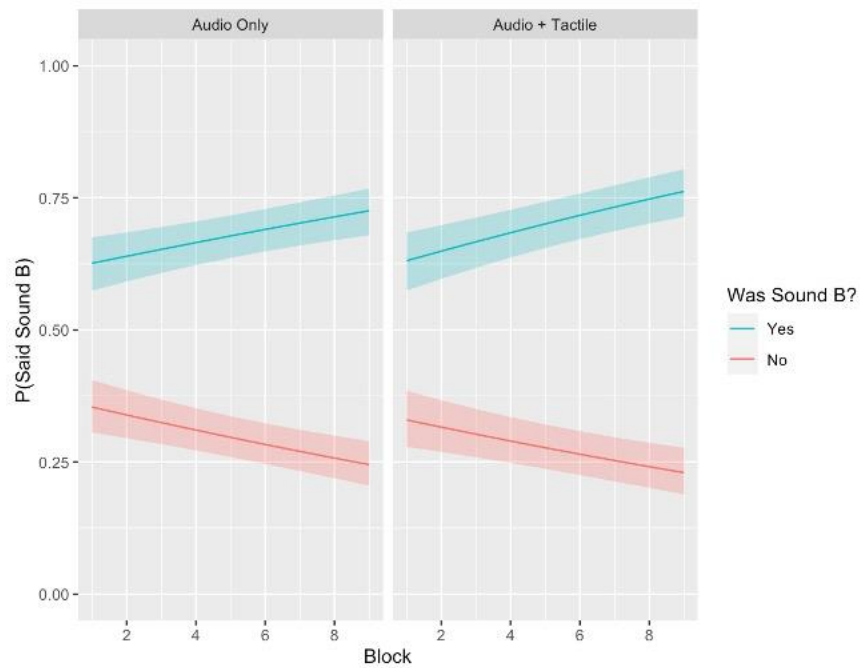

Figure 9. *Probability Said Sound B by Block and Was Sound B.*
Hit rate (green lines) and false alarms (red lines) across block and modality. Shaded error ribbons represent 95% confidence intervals. “Block” was mean-centered for analyses (c.Block).

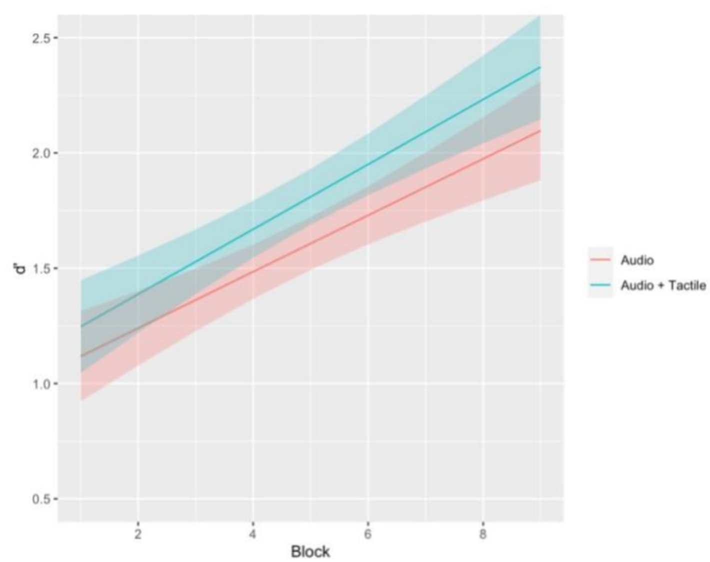

Figure 10. *Sensitivity (d’) Changes across Block and Modality.*
Shaded error ribbons represent 95% confidence intervals. “Block” was mean-centered for analyses (c.Block).

Discussion

Participants were able to learn to categorize exemplar sound patterns that were arbitrarily assigned to categories, rather than categorizing stimuli based on modality or some other rule. In particular, we saw greater sensitivity for auditory-tactile trained patterns compared to auditory-only. This finding in particular replicates the trend that was seen in EXP 1. However, here it cannot be accounted for by preexisting individual differences. Though participants had greater sensitivity on average for auditory-tactile trained patterns, they still did not have a differential increase in the rate of this sensitivity compared to auditory-only patterns throughout the task. Even so, that the sounds were arbitrarily assigned indicates that the difference must have been learning related. It is possible that the difference appeared very quickly during the process, thus showing up as a difference already in block 1.

Chapter 5 - Experiment 2B: Pattern Detection in Noise

Experiment 2B sought to explore if the effects of the multimodal auditory-tactile trained patterns would generalize to an auditory detection task. Previously, it has been found that synchronous vibro-tactile stimulation enhances detection of weak sounds in white noise (Gillmeister & Eimer, 2007). So, it was hypothesized that it may be possible that with multimodal training, we can also increase auditory detection. Specifically, we asked if the better learned patterns for the categorization task were more easily detected in noise.

Methods

Participants. The same subjects for EXP 2A took part in EXP 2B immediately following EXP 2A's completion.

Equipment. All equipment use was the same from EXP 1.

Stimuli. The patterns used for EXP 2A were the same used for EXP 2B. In addition, novel random patterns were generated on each trial using the same constraints.

1i-2AFC Perceptual Detection Task. Participants completed a 1-interval 2 alternative forced choice task in which the sound was presented through speakers (to the left & right of the computer monitor in front of the participant). Two types of stimuli could be presented. Either a stream of 20 consecutive patterns could be presented with 19 random and 1 trained previously (no repeats trial type), or a stream of 20 patterns with every other pattern being one of the previously trained patterns could be presented (some repeats trial type). Participants were tasked to discriminate “no repeat” trials from “some repeat” trials. In half of the trials, the pattern was repeated. Participants received feedback of their performance in percent correct at the end of each block. Participants completed a total of 192 trials of this task (48 trials per sound pattern, with 24 being repeated).

Statistics. Again, a multilevel logistic regression with a Probit link function was used to calculate *d'* and negative bias (-*c*). In the analyses, trained stimulus modality (Auditory-Only vs. Auditory-Tactile from EXP 2A) was treated categorically and effect coded with Auditory-Only as the contrasting condition. A new parameter, Was Repeat was included into the model to represent sensitivity. Was Repeat was treated as a continuous variable and re-coded as -0.5 or +0 .5, for 'not present' or 'present' respectively. Block was treated as continuous, and centered to its average to account for possible multicollinearity. The data were modeled using Modality, 'Was Repeat', and Block as fixed effects to predict Said Repeat. All possible RE models were run, and it was established that the RE model with Modality and Intercept slopes produced the best fit (*AIC*=7,070).

We predicted that:

H1: Detection sensitivity (as measured by *d'*) of repeats would improve across blocks (i.e. learning)

H2: The rate of improvement will vary across modality; Specifically that auditory-tactile trained patterns will have a greater improvement in detection sensitivity across blocks compared to auditory-only.

Results

It was found that Was Repeat was a significant predictor of Said Repeat in the model (β = 0.88, SE=0.04, p <.001), meaning participants were sensitive to the detecting the patterns, and understood the task. There was also a significant interaction between Was Repeat and Block (β =0.11, SE = 0.02, p =<.001) showing that participants' detection rate improved across Block as predicted in hypothesis 1 (see *Figures 11-12* and *Appendix B: Table 3*). Unlike EXP 2A, there was no Was Repeat x Modality interaction found here. So, there was no difference in detection between training Modality on average. We also found no significant Was Repeat x Block x Modality interaction as we predicted in hypothesis 2; so, there was no difference in the rate of improvement in detection across blocks between previously trained stimulus modality.

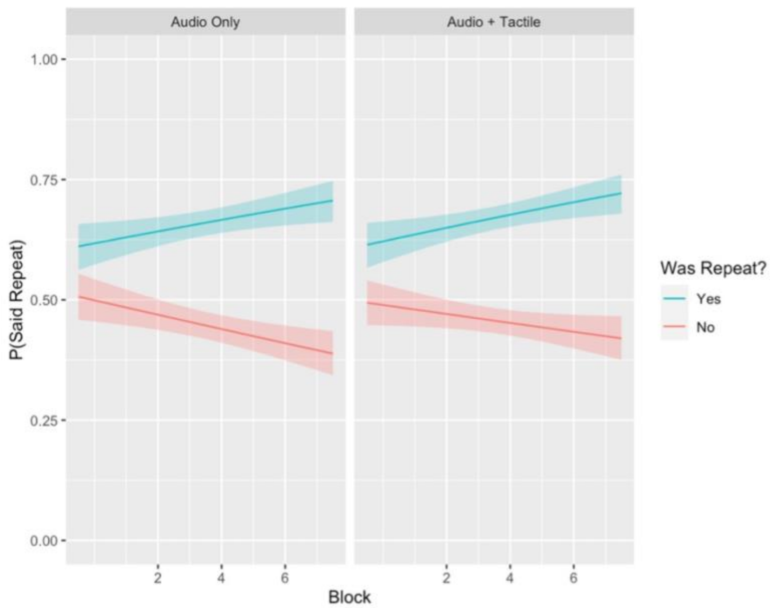

Figure 11. *Probability Said Repeat by Block and Was Repeat.*
Hit rate (green lines) and false alarms (red lines) across block and modality. Shaded error ribbons represent 95% confidence intervals. "Block" was mean-centered for analyses (c.Block).

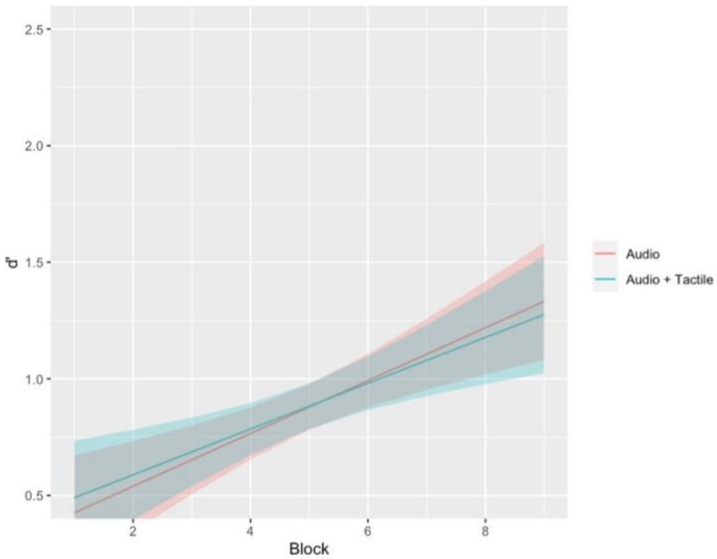

Figure 12. *Sensitivity (d') Changes Across Block and Modality.*
Shaded error ribbons represent 95% confidence intervals. "Block" was mean-centered for analyses (c.Block).

Discussion

Sensitivity increased across block, so participants learned to better detect repeats patterns in the sound. However, we saw no effect of training modality or interactions with training modality as predicted. This may have been due to the task being relatively difficult as *d'* values started around ~+0.5 in the experiment. Another factor that played a role was that our participants weren't detecting a sound in white noise as in Gillmeister & Eimer (2007), but were having to detect repeats of the learned pattern. This repeat detection is likely more difficult than detecting a sound in white noise.

Chapter 6 - Experiment 2C: Multisensory Categorization Training

This experiment was conducted to determine if we could replicate the effects of Experiment 2A. Here, we increased the amount of trials and number of patterns to learn as participants' sensitivity was starting to approach ceiling in the previous experiment.

Methods

Participants. A total of 17 college students were recruited at Kansas State University (Manhattan, KS). Students were undergraduates and consisted of ages 18 to 20 (M_{Age}= 18). Participant recruitment, sign-up, and consent process was the same as EXP 1. Participants that did not have normal hearing, or performed below chance (50% accuracy) were excluded from analyses. All participants in the study reported to have normal hearing, and performed above chance level; so, no participants met our exclusion criteria.

Equipment. All equipment use was the same from EXP 1.

Stimuli. Auditory stimuli from EXP 2A were used, along with an additional 4 sound patterns with the same parameters.

Tactile Calibration. Tactile calibration protocols and equipment are the same as EXP 1. Range of participants' voltage included: 11V- 32V (*M* = 17V; *Median* = 16V).

1i-2AFC Perceptual Categorization Task. Participants completed the same task used in EXP 2A. They completed a total of 432 trials of this task (54 trials per sound pattern) across 9 blocks.

Statistics. Analyses were conducted the same as EXP 2A. All possible RE models were run, and the model reported here contained Modality and Intercept slopes as REs (*AIC= 8,120*).

We predicted that:

H1: Sensitivity (as measured by *d'*) would improve across blocks (i.e. learning)

H2: The rate of improvement will vary across modality; Specifically that auditory-tactile will have a greater improvement in sensitivity across blocks compared to auditory-only.

Results

The variable Was Sound B was a significant predictor of Said Sound B in the model (β = 0.70, SE=0.03, p <.001), meaning participants were sensitive to the stimulus categories, and understood the task. Notice the beta weight is about half the size here as it was in EXP 2A as we doubled the number of stimuli to learn, making this task harder. There was a significant effect of Modality in this case, with the beta weights revealing that participants were more likely to label Auditory-Only stimuli as Sound B compared to Auditory-Tactile, (β =0.11, SE = 0.03, p =<.001). Again, we found a significant interaction between 'Was Sound B' and Block (β =0.03, SE = 0.01, p =.012) showing that participants' performance improved across Block as predicted in hypothesis 1 (see *Figures 13-14* and *Appendix B: Table 4*). We also observed a significant interaction between 'Was Sound B' and Modality (β = 0.14, SE = 0.03, p < .001), showing a significant difference in sensitivity between Auditory-Only and Auditory-Tactile stimuli. Interestingly, this interaction went in the opposite direction of what it did before in EXP 2A. Participants actually had worse sensitivity at categorizing Auditory-Tactile stimuli compared Auditory-Only (see *Figure 14*). Lastly, there was no Was Sound B x Block x Modality interaction as hypothesized.

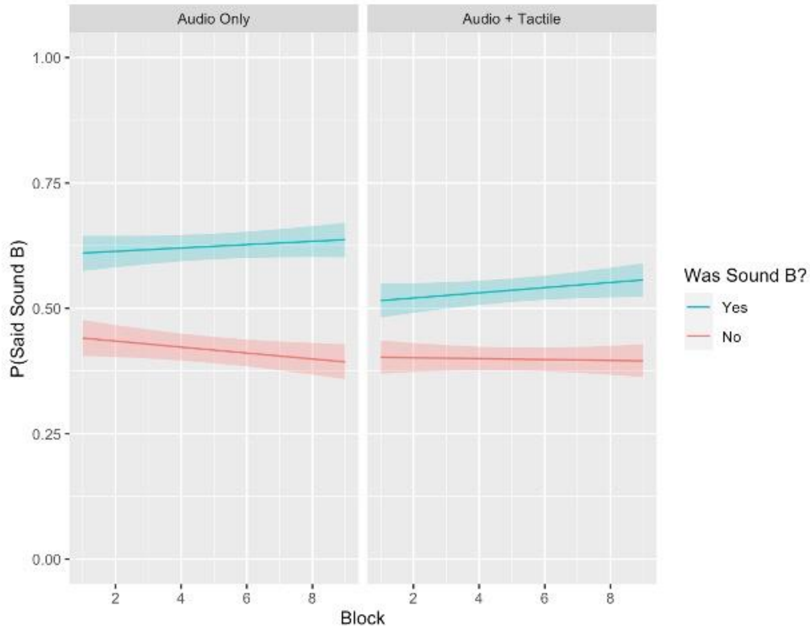

Figure 13. *Probability Said Sound B by Block and Was Sound B***.**
Hit rate (green lines) and false alarms (red lines) across block and modality. Shaded error ribbons represent 95% confidence intervals. “Block” was mean-centered for analyses (c.Block).

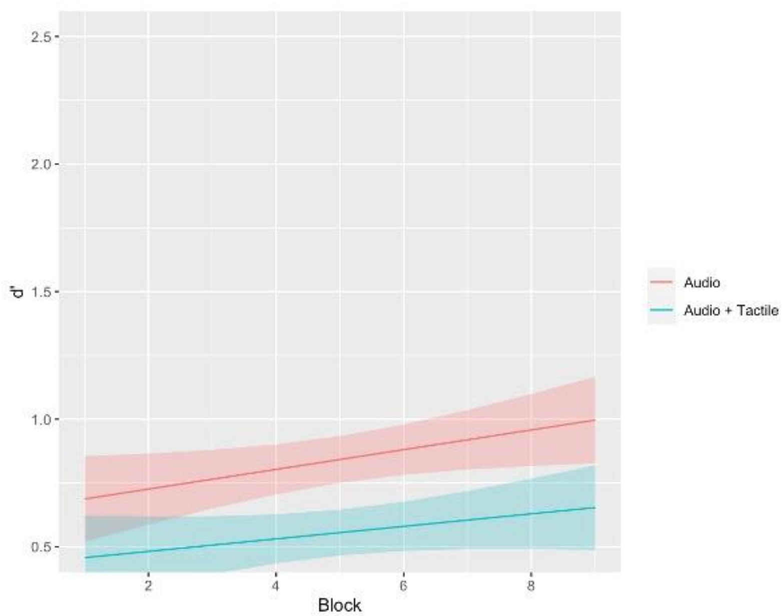

Figure 14. *Sensitivity (d’) Changes Across Block and Modality.*
Shaded error ribbons represent 95% confidence intervals. “Block” was mean-centered for analyses (c.Block).

Discussion

Learning occurred as sensitivity increased significantly across block, though we saw this for both auditory-only and auditory-tactile trained patterns. This time, the auditory-only patterns actually had an increased *d'* value on average compared to auditory-tactile patterns. This was the opposite of the Modality effect that we observed in EXP 2A. This may have resulted due to the increase of difficulty of the task since we doubled the amount of patterns to learn (hence the lower sensitivity levels). If this was the case, it may indicate limits in multimodal enhancement depending on difficulty or cognitive load. A noticeable difference between EXP 2A and 2C are the differences between hit and false alarm rates between auditory-only and auditory tactile (see *Figures 9 & 13*). Though not statistically tested, the slopes of the auditory-tactile hit rate and false alarm rate appear much shallower compared to the auditory-only in EXP 2C. The false alarm rate, in particular, appears almost flat for auditory-tactile trained patterns, which may indicate the learning (Block) effect observed in this experiment was driven more so by the auditory-only trained patterns compared to the auditory-tactile.

Besides difficulty and cognitive load, another factor that could have contributed to our observation of opposite Modality effects in EXP 2C compared to EXP 2A is fatigue differences. As EXP 2C had 8 sound patterns to learn, it inherently had more trials in the experiment (432 trials) compared to the 4 sound patterns in EXP 2A that had to be learned (180 trials). With prolonged stimulation, it is known that absolute perceptual thresholds increase over time, and this shift in threshold occurs more quickly and at a steeper rate for tactile compared to audition (Merchel & Altinsoy, 2020). So, we may have observed perceptual fatigue of tactile thresholds which then impacted auditory-tactile learning. If the tactile thresholds were increased from fatigue of prolonged stimulation, then the auditory-tactile training likely did not benefit perceptual learning. Tactile-only trained stimuli were not included in this particular study to test this possible explanation.

Overall, performance in this experiment was decreased as participants were tasked with learning 8 sound patterns compared to 4. We still saw no overall multimodal enhancement effect in sensitivity, and began to question the integration of the auditory-tactile stimulation. It may be that the tactile stimulation in the case of these sound patterns was actually just redundant and not meaningful, or that the location differences in the auditory and tactile stimulation were causing issues with spatial integration.

Chapter 7 - Experiment 3A: Temporal Thresholding

Experiment 3A and 3B both attempted to better integrate the auditory-tactile stimuli. We attempted to better integrate the stimuli spatially by switching our previous auditory set-up so that now the sound is only heard out of the right speaker, as the electrotactile stimulation occurs on the index finger of the right hand. Furthermore, we sought to explore if even a perceptual effect could be found when comparing auditory and auditory-tactile thresholds. That is, since learning effects appeared difficult to observe consistently, we chose to investigate whether we could get any perceptual facilitation effect at all. Previous studies have indicated that multisensory thresholds should be lower compared to unisensory thresholds (Raposo et al., 2012; Spence, 2016).

Methods

Participants. A total of 20 college students were recruited from Kansas State University (Manhattan, KS). Students were undergraduates and consisted of ages 18 to 24 (M_{Age}= 19). Participant recruitment, sign-up, and consent process was the same as EXP 1. Participants that did not have normal hearing, or performed below chance ($d' \leq 0$) were excluded from analyses. All participants in the study reported to have normal hearing. Two participants performed below chance level, and were removed from analyses as they did not meet our criteria; this resulted in a total of 18 participants.

Equipment. All equipment use was the same from EXP 1, besides the speakers. The auditory stimuli were only presented through the Mackie CR3-X speaker (Mackie, Bothwell, Washington) to the right of the experimental GUI screen.

Stimuli. Stimuli consisted of 6- 1kHz tone bursts having 100ms durations. The inter-stimulus-interval (ISI) varied between these bursts in a way to give the perception of the stimulus speeding up or slowing down. Stimuli that started with larger ISIs and ended with shorter ISIs were 'Speeding Up' stimuli, and the reverse were 'Slowing Down'. The minimum possible ISI was 10ms, and was held constant throughout the experiment, whereas the maximum ISI started at 80ms and then varied based on the participant's response to either make the next trial harder or easier.

Tactile Calibration. Tactile calibration protocols and equipment are the same as EXP 1. Range of participants' voltage included: 18V- 78V (*M*= 31V; *Median*= 29V). Electrotactile stimulation coincided with the noise bursts on half of the trials.

1i-2AFC Perceptual Threshold Task. Participants completed a 1-interval 2 alternative forced choice task in which the sound was presented through the right speaker. Participants had to categorize the noise/burst stimuli as 'Slowing Down' or 'Speeding Up'. In half of the trials, the noise burst was accompanied by simultaneous electrotactile stimulation. Participants received feedback of their performance directly after each trial as to test perceptual discrimination and not just arbitrary category response learning. Stimulus modality was blocked so that participants would complete auditory-only noise bursts or auditory-tactile bursts trials in consecutive adaptive tracks. This was necessary, as we used a Single Interval Adjustment Matrix (SIAM) to adjust the maximum ISI to find their ~75% threshold level needed to discriminate 'Slowing Down' from 'Speeding Up' for each stimulus modality (AO or AT). This adaptive procedure is relatively bias-free, and has been well established as a way to measure absolute thresholds (Kaernbach, 1990; Shepherd et al., 2011). We used 2.5ms step- sizes. If participants had a false alarm on the trial, the maximum ISI would increase 4 times the step-size (for a total of 10ms) for the next trial so that it was easier. A miss would result in the maximum ISI increasing 3 times the step size (for a total of 7.5ms). A hit resulted in the maximum ISI decreasing by the step-size

(2.5ms), and a correct rejection would leave the maximum ISI unchanged. The step-size was chosen as a baseline to pilot, but the rates at which the step-size was changed and added on to the maximum ISI for the next trial was the recommended usage of the SIAM procedure to hold the participant at ~75% accuracy (Kaernbach, 1990; Shepherd et al., 2011). A total of 240 trials (120 AO & 120 AT) were split across a total of 4 blocks, with half of the trials in each block consisting of ‘Slowing Down’ and half consisting of ‘Speeding Up’ trials.

Statistics. Each participant’s last 4 reversals of each block were used to grab the maximum ISI for that trial. Reversals were trials in which the direction ("Slowing Down" or "Speeding Up") switched. In essence, the lowest maximum ISI's of the last 2 "Slowing Down" and the last 2 "Speeding Up" trials were extracted from each block. These 4 maximum ISI's were then averaged to get the average maximum ISI needed to be able to discriminate between ‘Slowing Down’ and ‘Speeding Up’ stimuli. Each participant’s average maximum ISI for each block was then input into a linear mixed effects model. Each participant’s average maximum ISI for each block was then input into a linear mixed effects model. Block was treated as continuous, and centered to its mean to account for multicollinearity. Stimulus Modality was treated as categorical and effect coded so that the Auditory-Only stimuli was the contrasting condition. Modality and Block were then used to predict Threshold. All possible RE models were run, and it was established that the RE model with Modality and Intercept slopes produced the best fit (*AIC*=-386).

We predicted that:

H1: Maximum ISI thresholds would decrease across the experiment (i.e. participants would learn to discriminate between ‘Slowing Down’ and ‘Speeding Up’ stimulus bursts).

H2: The rate of decreased maximum ISI threshold would vary across modality; Specifically that audio-tactile stimulus bursts will have a greater decrease in threshold across blocks compared to auditory-only.

Results

Participants did learn to differentiate between 'Slowing Down' and 'Speeding Up' stimuli, as their Maximum ISI Threshold decreased across Block, (β = -8.24e^{-3}, SE=3.92e^{-3}, p =.04; see *Figure 15* and *Appendix B: Table 5*). There was no significant effect of Modality. Interestingly, we did find a significant Block x Modality interaction as predicted in hypothesis 2, (β = -0.01, SE= 5.54e^{-3}, p = .04). However, this interaction likely occurred as there was actually a large difference in the first block's maximum ISI threshold between modalities with the Auditory-Tactile needing a much higher threshold. This high maximum ISI then decreased to approximately the same level threshold in the last block as the Auditory-Only threshold.

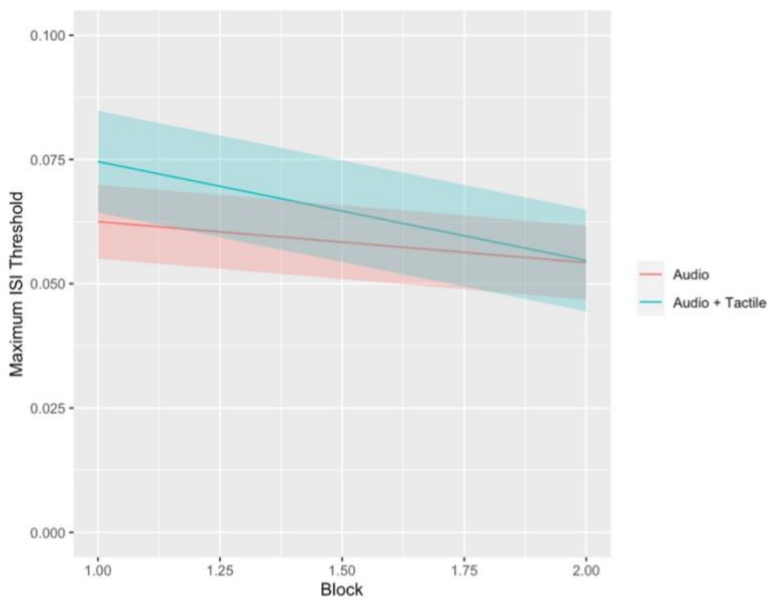

Figure 15. *Maximum ISI Threshold Changes Across Block and Modality.*
Shaded error ribbons represent 95% confidence intervals. "Block" was mean-centered for analyses (c.Block).

Discussion

We did get the interaction between block and modality that was expected; however, this interaction actually showed that there was a disadvantage at first in auditory-tactile thresholds compared to auditory-only. This perceptual disadvantage then disappeared with training. Though unexpected, this perceptual disadvantage may be supported by cross-modality masking findings in which both tactile and auditory stimuli are more likely to mask each other as a function of their presentation, with simultaneous presentations having the largest amount of masking (Gescheider & Niblette, 1967). It is possible that the lack of multimodal enhancement effect here is due to either the auditory or tactile system inhibiting or blocking the processing of the other. If this is the case, then the auditory-tactile stimulation used are not integrated.

Chapter 8 - Experiment 3B: Temporal Thresholding

This experiment sought to replicate EXP 3A, as well as explore this threshold training in more length. It may be possible that the benefits of crossmodal training just take longer to appear. So, this experiment extended the number of training trials, and blocks in the experiment to explore this training over time.

Methods

Participants. A total of 18 college students were obtained at Kansas State University (Manhattan, KS). Students were undergraduates and consisted of ages 18 to 23 (M_{Age}= 19). Participant recruitment, sign-up, and consent process was the same as EXP 1. Participants that did not have normal hearing, or performed below chance ($d' \leq 0$) were excluded from analyses. All participants in the study reported to have normal hearing. Two participants performed below chance level, and were removed from analyses as they did not meet our criteria; this resulted in a total of 16 participants.

Equipment. All equipment was the same as EXP 3A.

Stimuli. The same stimuli from EXP 3A were used.

Tactile Calibration. Tactile calibration protocols and equipment are the same as EXP 1. Range of participants' voltage included: 18V- 56V (*M* =30V; *Median*= 28V). Electrotactile stimulation coincided with the noise bursts on half of the trials.

1i-2AFC Perceptual Threshold Task. The same task was used from EXP 3A, though adjustments of 5ms were used rather than 2.5ms steps. Using a larger step size can allow for more reversals to occur. In EXP 3A, some of our participants only had 3 reversals. The analysis previously used can easily account for missing data, but the step size was increased to mitigate the amount of missing data we had for each participant. Participants also completed this task for 8 blocks (4 of each modality) rather than 4 blocks total.

Statistics. Each participant's last 4 reversals of each block were used to grab the maximum ISI for that trial. Reversals were trials in which the direction ("Slowing Down" or "Speeding Up") switched. In essence, the lowest maximum ISI's of the last 2 "Slowing Down" and the last 2 "Speeding Up" trials were extracted from each block. These 4 maximum ISI's were then averaged to get the average maximum ISI needed to be able to discriminate between 'Slowing Down' and 'Speeding Up' stimuli. Each participant's average maximum ISI for each block was then input into a linear mixed effects model. Block was treated as continuous, and centered to its mean to account for multicollinearity. Stimulus Modality was treated as categorical and effect coded so that the Auditory-Only stimuli was the contrasting condition. Modality and Block were then used to predict Threshold. All possible RE models were run, and it was established that the RE model with Block and Intercept slopes produced the best fit (*AIC*=-648).

We predicted that:

H1: Maximum ISIs would decrease across the experiment (i.e. participants would learn to discriminate between 'Slowing Down' and 'Speeding Up' stimulus bursts).

H2: The rate of decreased maximum ISI threshold would vary across modality; Specifically that audio-tactile stimulus bursts will have a greater decrease in threshold across blocks compared to auditory-only.

Results

Learning to differentiate between Slowing Down and Speeding Up stimuli did occur as participants' Maximum ISI Threshold decreased across Block, (β = -6.46e^{-3}, SE=2.06e^{-3}, p =.002; see *Figure 16* and *Appendix B: Table 6*). There was no significant effect of Modality, nor a Block x Modality interaction. Overall, participants' thresholds decreased throughout the experiment for both auditory and auditory-tactile stimuli.

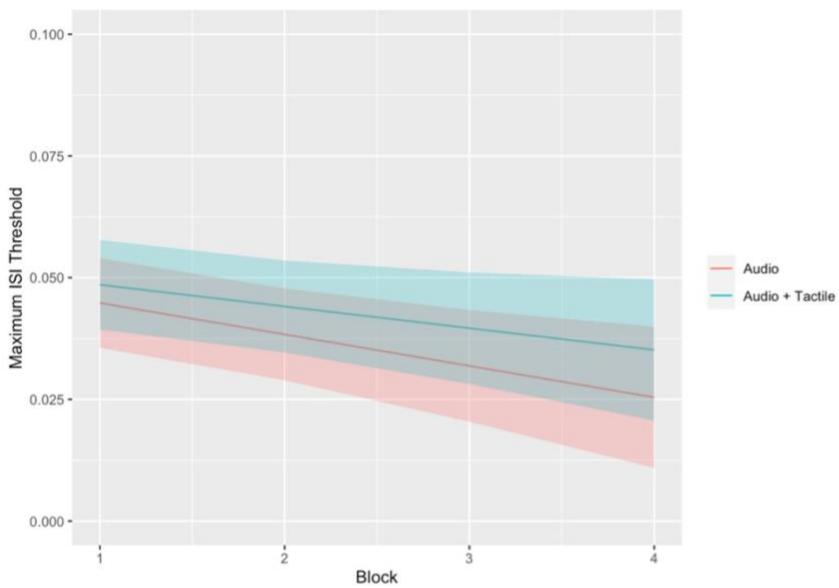

Figure 16. *Maximum ISI Threshold Changes Across Block and Modality*.
Shaded error ribbons represent 95% confidence intervals. "Block" was mean-centered for analyses (c.Block).

Discussion

Through-out training, thresholds decreased, indicating that participants can learn to differentiate from slowing and speeding stimuli with smaller differences over time. As participants were learning, larger decreases in threshold occurred early on and smaller changes toward the end of the experiment. This is typical in many learning paradigms. In previous studies, it may have appeared as if there was some interactions between multimodal-trained versus unimodal-trained stimuli as they may have only observed learning over a short period of time. For example, there appears to be a chance of a possible significant interaction if we observe the differences in threshold from the first to second block (see *Figure 16*). However, as the blocks continue to progress, it is more clear that there is no Modality x Block interaction. This dynamic represents points of early learning acquisition when behavior is relatively unstable (participants are learning based off of trial and error), and is not a stable dynamic to base any claims off of.

Chapter 9 - General Discussion

In summary, these experiments sought to explore crossmodal enhancement effects for auditory categorical, discrimination, and detection tasks after audio-tactile training. It was hypothesized that these benefits would occur as they have been found consistently in previous literature. Experiment 1 compared multimodal and unimodal trained groups' sensitivity changes pre- to post-test. Participants' sensitivity overall significantly improved pre-test to post-test, and there were no differences between modality training condition or test x modality interaction. Experiment 2A and 2C explored effects of auditory-tactile training in an auditory categorization task. Both of these experiments found a perceptual learning effect, and a modality effect; though the modality effect was in opposite directions. In EXP 2A sensitivity was overall greater for auditory-tactile stimuli compared to auditory-only, which was the same as the trend seen in EXP 1. However, in EXP 2C- sensitivity for auditory-tactile stimuli was worse compared to auditory-only stimuli overall. Experiment 2B tested the generalization of the training effects seen in EXP 2A to an auditory detection task. In this task, the learning effect was the only thing observed as with EXP 1. Lastly, Experiment 3A and 3B explored thresholds for auditory and auditory-tactile stimuli in a temporal discrimination task. Both experiments showed an overall learning effect as participants' thresholds significantly decreased across blocks, but EXP 3A did find a Block x Modality interaction. This was the only experiment that results showed an interaction of block/test with modality as was originally hypothesized (see *Table 1*), but seemed to occur due to an initially worse auditory-tactile threshold compared to auditory-only.

Table 1
Overall Experiment Results

Experiment	Title	Block/Test Effect	Modality Effect	Block/Test*Modality Interaction
1	Temporal Gap Judgement	*	n.s	
2A	MS Categorization Training	*	↑	
2B	Pattern Detection in Noise	*	n.s	
2C	MS Categorization Training	*	↓	
3A	Temporal Thresholding	*	n.s	*
3B	Temporal Thresholding	*	n.s	

Note. Significant effects are noted with an asterisk*. Significant modality effects use an arrow to specifiy if auditory-tactile were better (up) or worse (down) compared to auditory-only, and non-significant modality effects are abbreviated “n.s”.

In general, we found that participants can experience auditory-tactile stimulation and improve their sensitivity in temporal discrimination, thresholding, and general categorization tasks. We also saw that they could generalize this multisensory training to an auditory detection task, and improve their ability to detect repeats in a sound pattern. However, all of these effects were found for auditory-only trained stimuli as well. Though there have been numerous studies that have found crossmodal enhancement and MS training benefits, a recent study (Fu & Riecke, 2022) also found no enhancement effect of in-phase or anti-phase auditory-tactile (electrotactile) compared to auditory-only in performance on an auditory detection task. Though, they did find that in-phase auditory-tactile stimulation increased cortical activation in response to fluctuations of auditory noise occurred at a higher rate compared to auditory-only stimulation. Similarly, in an auditory detection paradigm we conducted recently, we found that participants were just as sensitive in detecting untrained sounds as trained sounds; yet, their auditory evoked potentials (AEPs) showed changes only to the trained sounds (Wisniewski et al., 2023). So, it could be that behavioral effects are lagging behind the neural effects of multisensory enhancement specifically with the somatosensory system. We could determine this by replicating the detection experiment done here (EXP 2B) with a pre-exposure phase in which participants are exposed to auditory-tactile and auditory-only stimulus patterns, and simultaneously examine auditory evoked potentials.

Whether behavior is “lagging” or if integration is an issue in this series of experiments- we are unsure. Multisensory integration occurs best when stimuli are temporally synchronous, spatially congruent, and at least one of the stimulus are weakly exciting a neuron (Holmes & Spence, 2006). All of our experiments used synchronous presentation, and EXP 3A and 3B both used spatially similar stimuli. Obviously, no physiology was measured in these experiments so we cannot know for a fact if either the auditory or tactile stimulation during AT presentations was weak. However, when we switched to using just the right speaker- the volume of our sounds decreased. So, we can predict that this may have affected neurons to react more weakly compared to before.

It is also possible that auditory-tactile stimuli are also just not as regularly integrated as some of the other sensory systems. The superior colliculus is a brain region consistently implemented in multisensory integration, with the deep laminae cell layers being most responsible (Meredith & Stein, 1986). Meredith & Stein (1986) analyzed 344 deep laminae cells and found that only 4% responded to auditory-tactile stimulation, while 29% responded to auditory-visual, and 10% to visual-tactile. With less neurons encoding this information, perhaps we just don’t as readily tend to combine information from auditory and somatosensory. Evolutionarily, our auditory system is typically related more towards a distal alert system with predators (Römer, 2016), whereas our somatosensory system is more proximal (Shang et al., 2019). This does not give either system more importance over the other, but may reflect differences in processing time or threshold levels in general. We may be cued more into relying on audition first, and then using tactile cues as it is generally better to hear and prepare (hide, run, etc.) for a predator rather than get eaten or have to fight. This could explain why we saw auditory-tactile thresholds were initially disadvantaged over auditory-only thresholds.

Besides integration, another more applied factor is the issue of attention. In particular, several multimodal enhancement effects involving the somatosensory system have been found when using haptic or active movement (Junker et al., 2021; Su & Pöppel, 2011). In the experiments reported here, passive tactile stimulation is used. The participant does not have to actively move or touch something- they just get a shock delivered to their finger. When experiencing everyday life, we tend to pay attention to things we're reaching for, grabbing, etc. However, we do not tend to think about the more passive somatosensory touches such as how our shirt feels on our back or how our socks are touching are feet (that is, until I just pointed those out to you). It is possible that we do this so that our somatosensory system does not get overwhelmed; we have learned to "tune out" more of the passive stimulations as to focus on whatever is currently relevant. Moreover, by ignoring these everyday passive tactile stimulations, we are better able to extract relevant information from various sensory modalities (multisensory selection problem; Spence, 2002). So, when participants' sensitivity didn't increase more for AT trained stimuli over time compared to AO, it may have been because the tactile in the AT was "tuned out", effectively creating it no better than the AO condition. These particular experiments were not designed to assess the workings of the somatosensory system's attention and interactions with auditory attention so cannot making any concrete claims; for review of somatosensory attention and multimodal interactions with attention, see the following (Spence, 2002; Mima et al., 1998; Fugiwara et al., 2002; Forster & Eimer, 2005).

One other reason we may not have seen multimodal enhancement may be due to the phrasing of our instructions in our tasks. We asked participants to determine what the whole stimulus was doing rather than just the auditory or just the tactile, like many other studies have done (Liu et al., 2011; Lui, 2012). This may have caused an increase in cognitive load that negatively affected perception. This might explain why auditory-tactile thresholds were so much larger compared to auditory-only in the beginning of our experiments as well. When asking what the stimulus is doing, participants are trying to perceive both sensations at once, which is distracting from the other. In the future, we could change our paradigm so as to only ask about the auditory stimulus or to specifically ignore the tactile sensation. This would be interesting to see if any of our tasks might see this enhancement just from a change in procedural directions. In that case, it may mean that multimodal stimuli are only helpful when they are congruent, and support another stimulus; otherwise, they may work as an inhibitor to perception.

This work overall has expanded on the small amount of literature regarding the somatosensory domain (particularly when using electrotactile stimulation) and its effects on audition. It overall supports an initial disadvantage of auditory-tactile training on auditory perception that is weakened with training. Future studies should explore this further to understand if this case is distinct to electrotactile stimulation or is actually representative of all auditory-tactile stimulations. Training periods could also occur over longer or multiple time periods to understand the progression of these learning effects.

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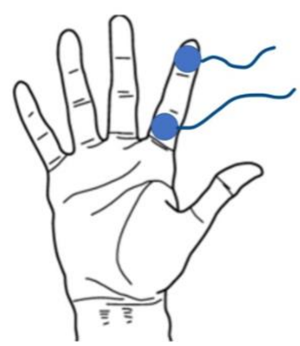
Appendix A - Tactile Calibration

Manual Step By Step Tactile Calibration:

1. Make sure Tactile System is "ON", and the black box that connects the output to the black box inside the booth is in "ON" position BEFORE the participant is hooked up. Flip on the light above system (top right of technology storage box) so that you can clearly see the voltage numbers on dial.
2. Set the Voltage dial to "0" by turning the dial all the way to the left.
3. Complete Participant Tactile Set-Up written below.
4. Threshold: **"Anything?"**
    a. Ask participant to let you know when they feel something after every shock. Use the single Trigger button to give one shock. Start at '0', and then turn the dial to the right to increase the shock by .5 (actually 5 volts) and deliver shock until the participant says they feel something. Write this down as "threshold" (i.e. 40).
5. Annoying: **"Up or Stop?"**
    a. Ask participant to let you know whether they want to go "Up or Stop", and let them know that they should stop when the stimulus becomes annoying, but not painful. Proceed using the single trigger button, turning the dial up by .5 (5 volts). When the participant says "Stop", write this number down as the "annoying" level (i.e. 45).
6. Actual Voltage:
    a. Turn dial to the left (down) by .2 (2 volts), and use this level in the experiment (i.e. if the participant said 45 was annoying, then 45-2 = 43. Use 43 as the Actual Voltage). Write this level down as the "Actual Voltage" used.
7. Continue to monitor participant, and adjust voltage if necessary after the first few trials. Make a note of any adjustment after experiment has begun (past the first few trials). (You'll likely have to increase the voltage so that the stimulus is more detectable- try going up 2V if they ask to have it up… if you need to decrease-> make sure it stays at least 2V above the threshold level).

Participant Tactile Set-Up:

Equipment needed: Electrode wires (Green/Blue & Yellow/Black), single use sticky electrodes Medical Tape, Alcohol Pad



1. Have participant sanitize hands upon arrival.
2. Clean the palm side of the participant's right index (pointer) finger with an alcohol pad.
    a. Note. If participant has open cut/wound (or healing)→ try to place electrodes NOT on the cut. If that is not possible, use middle finger on right hand & make note of it on subject condition sheet.
3. Stick single use electrodes on the most distal and proximal pads of the index finger & Plug them into the electrode wires.
4. Tape electrode wires to the inner right forearm, and plug wires into output box inside booth. It does not matter which electrode is plugged into which output.

Appendix B - Supplemental Tables

Appendix B Table 1

Parameter Estimates for Predictors of Said Fast

Predictor	β_x	*SE*	*z*	*p*
Intercept (Bias)	0.08	0.03	3.07	.002
Was Fast (Sensitivity)	1.19	0.03	47.05	$<2e^{-16}$
Modality	0.01	0.03	0.48	.633
Test	0.04	0.01	2.96	.003
Was Fast x Modality	-0.04	0.03	-1.75	.080
Was Fast x Test	-0.08	0.03	-3.31	$9.25e^{-4}$
Test x Modality	$7.94e^{-3}$	0.01	0.63	.528
Was Fast x Test x Modality	$1.30e^{-3}$	0.03	0.05	.959

Note. GzLME results from EXP 1: "Temporal Gap Judgement".

Appendix B Table 2

Parameter Estimates for Predictors of Said Sound B

Predictor	β_x	*SE*	*z*	*p*
Intercept (Bias)	-0.06	0.03	-1.68	.093
Was Sound B (Sensitivity)	1.71	0.04	40.36	$<2e^{-16}$
Modality	$-2.66e^{-3}$	0.09	-0.03	.977
Block	$1.95e^{-3}$	0.01	0.25	.803
Was Sound B x Modality	-0.10	0.04	-2.39	.017
Was Sound B x Block	0.13	0.02	8.41	$<2e^{-16}$
Block x Modality	$-6.13e^{-3}$	0.01	-0.79	.433
Was Sound B x Block x Modality	$-9.19e^{-3}$	0.02	-0.59	.557

Note. GzLME results from EXP 2A: "Multisensory Categorization Training".

Appendix B Table 3

Parameter Estimates for Predictors of Said Some Repeats

Predictor	β_x	*SE*	*z*	*p*
Intercept (Bias)	0.25	0.05	5.31	$1.10e^{-7}$
Was Repeat (Sensitivity)	0.88	0.04	25.04	$<2e^{-16}$
Modality	-0.02	0.02	-1.03	.304
Block	4.13^{-3}	0.01	0.40	.687
Was Repeat x Modality	-1.91^{-3}	0.04	-0.05	.957
Was Repeat x Block	0.11	0.02	5.15	$2.63e^{-7}$
Block x Modality	-7.59^{-3}	0.01	-0.74	.460
Was Repeat x Block x Modality	7.58^{-3}	0.02	0.37	.712

Note. GzLME results from EXP 2B: "Pattern Detection in Noise".

Appendix B Table 4

Parameter Estimates for Predictors of Said Sound B

Predictor	β_x	*SE*	*z*	*p*
Intercept (Bias)	-0.02	0.03	-0.70	.482
Was Sound B (Sensitivity)	0.70	0.03	21.32	$<2e^{-16}$
Modality	0.11	0.03	3.46	$5.47e^{-4}$
Block	$1.69e^{-3}$	$6.32e^{-3}$	0.27	.789
Was Sound B x Modality	0.14	0.03	4.38	$1.21e^{-5}$
Was Sound B x Block	0.03	0.01	2.50	.012
Block x Modality	$-6.81e^{-3}$	$6.32e^{-3}$	-1.08	.282
Was Sound B x Block x Modality	$7.03e^{-3}$	0.01	0.56	.578

Note. GzLME results from EXP 2C: "Multisensory Categorization Training".

Appendix B Table 5

Parameter Estimates for Predictors of Threshold

Predictor	β_x	*SE*	*t*	*p*
Intercept	0.06	$2.95e^{-3}$	19.76	$6.88e^{-30}$
Modality	$6.25e^{-3}$	$3.27e^{-3}$	1.91	.060
Block	$-8.24e^{-3}$	$3.92e^{-3}$	-2.10	.039
Block x Modality	-0.01	$5.54e^{-3}$	-2.11	.039

Note. LME results from EXP 3A: "Temporal Thresholding".

Appendix B Table 6

Parameter Estimates for Predictors of Threshold

Predictor	β_x	*SE*	*t*	*p*
Intercept	0.05	$4.99e^{-3}$	10.27	$2.78e^{-18}$
Modality	$1.74e^{-3}$	$2.72e^{-3}$	0.64	.522
Block	$-6.46e^{-3}$	$2.06e^{-3}$	-3.13	.002
Block x Modality	-0.01	$2.43e^{-3}$	0.82	.412

Note. LME results from EXP 3B: “Temporal Thresholding”.