

Towards understanding the neural mechanisms of haptic communication

Alix S. Macklin, Simon J. Fischer-Baum, Jeffrey M. Yau, Marcia K. O'Malley, *Senior Member, IEEE*

Keywords—*Haptic-communication, multimodal cues, language processing, EEG, Event related potentials*

I. BACKGROUND

Haptic communication is the ability to transmit information via touch. It provides a mode of communication for individuals with visual and/or auditory sensory deficits, as well as a mode of communication when visual and auditory inputs are preoccupied. Haptic language modes such as braille and tactile vocoders exist [1], and recently, research groups have developed wearable systems for haptic communication [1,2]. In particular, MISSIVE (Multi-featured Interface of Stretch, Squeeze, and Integrated Vibration Elements) transmits English phonemes to the user via multimodal, haptic cues [1]. Using the multimodal cues of lateral skin stretch, radial squeeze and vibrotactile stimuli, the MISSIVE, shown in Fig. 1, generates haptic cues that improve perceptual distinguishability compared to cues generated by solely vibrotactile components [1]. Although there is ongoing research exploring how the brain learns single-featured, vibrational encodings of speech as well as research investigating tactile perception of speech, little is known about how the brain processes multimodal cues during language transmission. Large complex cue sets required for language transmission may be best conveyed by a multi-featured mapping of cues [1] so it is imperative that we understand how these cues are processed in the brain to optimize future multi-featured, haptic-language devices and to better understand the neural correlates of language processing in general.

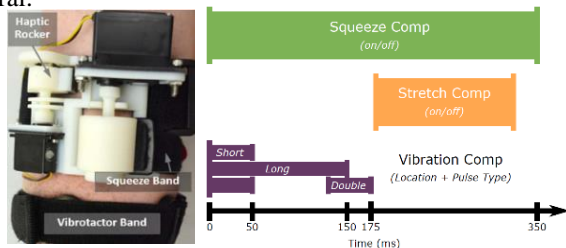


Figure 1. (Left) The MISSIVE device. The upper band includes the Haptic Rocker and the Squeeze Band, which render lateral skin stretch and radial squeeze sensations, respectively. The Vibrotactor Band utilizes four vibrotactors to render low, high, or double pulses on the top, right, bottom, or left side of the arm; (Right) Timing diagram for MISSIVE cues. Squeeze and stretch components can be on or off; vibration always occurs.

The Mismatch negativity (MMN) is a component of the time-locked neural response known as the event-related potential (ERP), extracted from non-invasive electroencephalography (EEG) recordings [3,4]. The MMN response is elicited by deviant cues in a typical oddball paradigm design in which a set of standard stimuli are infrequently interrupted by a deviant cue, such that the stimulus set is made up of 15% of deviants [3]. Specifically,

the MMN is the difference waveform between the ERP evoked by the deviant cue and the ERP evoked by the standard cue, and it reflects pre-attentive and automatic categorical processing of deviant sensory stimuli of auditory, visual, olfactory, and somatosensory modalities within and across categorical boundaries [4]. The MMN has been used to characterize both pre-attentive categorical processing of native phonemes as well as vibrational components [4], making it a strategic neural response to investigate training on MISSIVE. Prior to understanding how tactile language is processed at the pre-attentive level, we must understand how tactile cues independent of any mapping to language are processed at the neurological level. This is the essential first step to understanding the effect of phoneme specific training on MISSIVE and how training alters the MMN response to MISSIVE cues. In this paper, we first demonstrate that individuals form an automatic, categorical response to MISSIVE specific cues. Then, we evaluate how this response changes with phoneme-specific training on MISSIVE.

II. METHODS

To demonstrate automatic discrimination between non-linguistic, multimodal MISSIVE cues, we conducted a single-subject pilot study where EEG was used to record neural responses in an oddball paradigm study. The basis of the oddball paradigm is that a stream of frequently presented “standard” cues are interrupted by some infrequent oddball cue, termed the “deviant”, which differs from the standard cue by some distinct characteristic [3,4]. The automatic neural response to deviant cues is reflected in the MMN [3,4], therefore the subject does not need to attend to the presented stimuli. In a follow-up pilot study, we evaluated the MMN response to deviant MISSIVE cues before and after the subject completed 4 days of phoneme-specific training on MISSIVE [1]. Throughout training, the subject learned to associate unique MISSIVE cues to a set of 23 phonemes. We designed 4 sets of oddball paradigms to elicit the MMN response to deviant MISSIVE cues. The oddball blocks used to elicit the MMN in each study are laid out in Fig. 2. In each block, the deviant cues varied from standard cues by one degree of freedom in terms of where on the upper arm the vibration component of the MISSIVE cue was felt. Each cue in the first deviant cue set was mapped to a phoneme after training, however the second cue set remained unmapped.

We recorded EEG data with a 32 channel actiCAP (Brain Products GmbH, Germany) and preprocessed EEG data using the EEGLAB 14.1.2b toolbox [5]. Based on previous studies, the MMN to somatosensory stimuli (sMMN) is prominent in frontal-central and central scalp regions and is expected to peak around 90-190ms after stimulus onset [6]. Therefore, we analyzed neural recordings from four frontal, frontal-central, and centrally located electrodes, Fz, FC5, Cz and C3 electrodes. We averaged the neural activity across each electrode site for both the ERP to standard and deviant cues and calculated the overall difference waveform between the

A. S. Macklin, S.J. Fischer-Baum, and M.K. O'Malley are with Rice University, Houston, TX 77005 USA. (e-mail: am150@rice.edu, sjf2@rice.edu, omalley@rice.edu).

J. M. Yau is with the Baylor College of Medicine, Houston TX 77005 USA (e-mail: jeffrey.yau@bcm.edu).

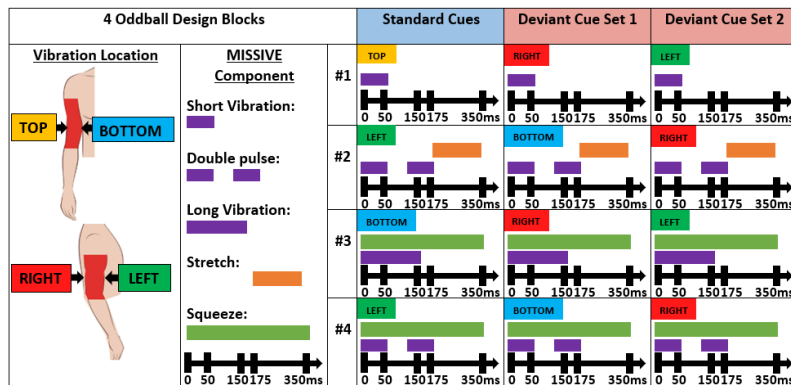


Figure 2. One standard cue and two deviant cues were used in each oddball paradigm in order to determine if deviant cues rendered by MISSIVE elicited a (somatosensory) MMN. Deviant cues varied from the standards in terms of where the vibrational component of the multimodal MISSIVE cue was felt.

deviant and standard ERPs, 100ms before and 300ms after the onset of stimulus cues.

In the first pilot, we evaluated the MMN response in the 90-190ms window after stimulus onset. The MMN to deviant MISSIVE cues is the difference waveform between the average ERP to deviant cues and the average ERP to standard cues over this specified time window. In the second pilot, we adjusted this time window to center around the most negative peak of the overall difference waveform found in the first pilot study. Specifically, we located the most negative peak between 0-300ms after stimulus onset and adjusted the time window to evaluate the MMNs, pre- and post- training, to be 100ms around this time point. For each study, we calculated the amplitude of the MMN according to Shen et al. We averaged the total neural activity over 20ms, 10ms before and 10ms after the occurrence of the most negative peak within the time windows we identified to evaluate the MMN responses for each pilot study [6].

III. RESULTS

Overall ERP waveforms to standard and deviant cues presented in the first study are plotted in Fig. 3, along with their respective difference wave. The neural activity 100ms before and 300ms after the onset of stimulus cues is shown. The time window marked by blue lines is the time period we evaluated the MMN response. The amplitude of the MMN was calculated by averaging the neural activity over a 20ms window surrounding the most negative peak of the overall MMN response, marked with an arrow on Fig. 3. The overall MMN amplitude to deviant cues rendered by MISSIVE was found to be $-0.81\mu\text{V}$.

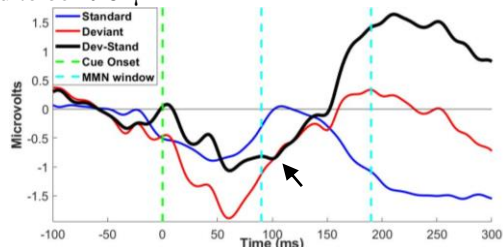


Figure 3. Neural activity recorded on Fz, FC5, Cz, and C3 electrodes were averaged to obtain the average ERP responses to standard and deviant

Overall ERP waveforms, collected in study two, to standard and deviant cues pre- and post- phoneme-specific training on MISSIVE are shown in Fig. 4. The neural activity, along with the difference waveforms are plotted 100ms before and 300ms after the stimulus onset of presented cues. As in study 1, standard and deviant cues from each oddball set were equally presented in the paradigms for both the pre and post training conditions. The MMN responses were evaluated in the time

window from 12ms to 112ms. This was based on the 100ms surrounding the most negative peak of the overall difference waveform in the first study, which was found to be $-1.065\mu\text{V}$, 62ms after stimulus onset. This updated time window is marked by blue lines in both plots of Fig. 4. The amplitude of the MMN response within this time window was found to be $-0.76\mu\text{V}$ in the pre-training condition and $-1.52\mu\text{V}$ in the post-training condition.

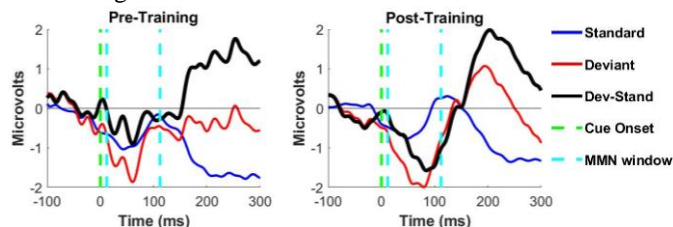


Figure 4. Neural responses before and after subject completed four days of phoneme-specific training on MISSIVE.

IV. DISCUSSION

In the presented pilot studies, we sought to determine if the MMN is a useful methodology to investigate the neural correlates of tactile language acquisition and processing. First, we characterized the MMN to deviant cues unmapped to linguistic context, presented on a multimodal, haptic device. Second, we determined how this automatic response to tactile stimuli changed once the user trained to associate certain MISSIVE cues with phonemes. The increase in MMN amplitude after the subject learned to associate 23 unique MISSIVE cues with phonemes suggests the MMN to deviant cues rendered by MISSIVE will reflect training effects by a greater negativity. While additional data collection and more rigorous analysis is needed, our initial findings suggest that the MMN is a suitable tool to investigate the neural correlates of language-specific learning on MISSIVE.

REFERENCES

- [1] Dunkelberger et al., "Conveying Language Through Haptics: A Multi-sensory Approach," in *Proceedings of the 2018 ACM International Symposium on Wearable Computers (ISWC '18)*, pp. 25–32, 2018.
- [2] Reed et al., "A Phonemic-Based Tactile Display for Speech Communication," in *IEEE Transactions on Haptics*, vol. 12, no. 1, pp. 2–17, 1 Jan.-March 2019.
- [3] S. J. Luck, *An Introduction to the Event-Related Potential Technique*. Cambridge, MA: MIT Press, 2014.
- [4] Näätänen et al., "The mismatch negativity (MMN) in basic research of central auditory processing: a review," *Clinical neurophysiology*, vol. 118, no. 12, pp. 2544–2590, December 2007.
- [5] Delorme et al., "EEGLAB: An open source tool- box for analysis of single-trial EEG dynamics including independent component analysis," *J Neurosci Methods*, vol. 134, no. 1, pp. 9–21, March 2004.
- [6] Shen et al., "Using somatosensory mismatch responses as a window into somatotopic processing of tactile stimulation," *Psychophysiology* pp: 1–14, 2017.