Cortical response to expectation of tactile stimulation from external anthropomorphic and non-anthropomorphic systems

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***Abstract*— Complete sensorimotor integration and user acceptance of a neural prosthesis relies on system embodiment – the incorporation of an external system into one's own body schema and representation. Embodiment of neural prostheses is an ambiguous concept with limited approaches for quantifying human and machine integration in a meaningful way. In an attempt to understand human sensory integration with external systems, we measured neural activity in the somatosensory cortex of a participant with chronically implanted microelectrode arrays during sensory events tied to either a virtual robotic hand touching an object or a virtual lamp lighting up. Sensory stimulation was delivered using either skin vibration or intracortical microstimulation (ICMS) and was mapped to the virtual systems. Through the brain-machine interface, we observed quantifiable cortical activity corresponding to tactile sensations perceived during the virtual tasks and even during instances when neural stimulation was expected but not delivered, demonstrating the presence of sensory-related neural activity even in the absence of tactile stimulation. Evoked sensory expectation signals were also observed in the motor cortex, although at reduced amplitudes. Evoked cortical activity corresponding to expectation of a sensory input could serve as objective cortical markers for better understanding sensorimotor integration and perceptual experiences when connecting humans with external systems.**

I. Introduction

Embodiment of a neural prosthesis is an ambiguous phenomenon and quantification relies on subjective questionnaires or behavioral responses. For prosthetic limbs, embodiment has been viewed in terms of body representation – the prosthesis being integrated and incorporated into one's body schema – or in terms of the subjective experience that the prosthesis is perceived as if it is a biological limb [1]. Within prosthesis embodiment exists subcomponents including but not limited to *ownership* - the perception that the device belongs to the individual, *agency* - the degree of voluntary control of the device, and *sensory integration* - the ability to intuitively perceive and interpret sensory events on or from the device [1], [2].

Feedback from skin vibration has been has been shown to increase perceived levels of embodiment of prosthetic limbs for individuals with arm amputation [3], [4]. Electrical stimulation of nerves, which can elicit sensations of touch in the phantom hand after amputation [5], [6], can also increase levels of embodiment - as measured by subjective questionnaires - during at-home use of a sensorized prosthesis [7]. For individuals using neural signals to interface with external systems, such as a remote controlled plane [8] or external robotic arms for bimanual self-feeding [9], incorporation into their body schemas is even more abstract and complex given that biological limbs are not being replaced, rather they are being augmented with external systems.

To better understand how users integrate external systems, we explored the role of sensory events caused by external systems in generating cortical activity in the somatosensory cortex of a human participant interfacing with both anthropomorphic and non-anthropomorphic systems. We aimed to use neural activity as an objective measure during expected sensory inputs caused by an external system. Neural activity in the motor cortex was recently shown to be affected by the perceived state of agency [10], and optical imaging in non-human primates during sensory illusion experiments shows that perception-related signals can be generated in brain regions representing areas where the illusion is experienced, despite no physical sensory stimulation of those regions [11]. These prior results suggest that cortical signals could be used as an objective metric for capturing components of embodiment, which could further aid in understanding sensorimotor integration of external systems.

II. Methods

A. Participant

A total of six microelectrode arrays (Blackrock Neurotech) were implanted in the left and right primary motor and somatosensory cortices in a male participant with a spinal cord injury (C5/C6, American Spinal Injury Association Impairment Scale Grade B) [12], [13]. For the experiments reported here, we used two microelectrode arrays (32-ch, 4 mm x 2.4 mm) with sputtered iridium oxide films (SIROF) in the left somatosensory cortex to record and stimulate neural activity (Fig. 1A). The 32-ch electrode arrays were located in

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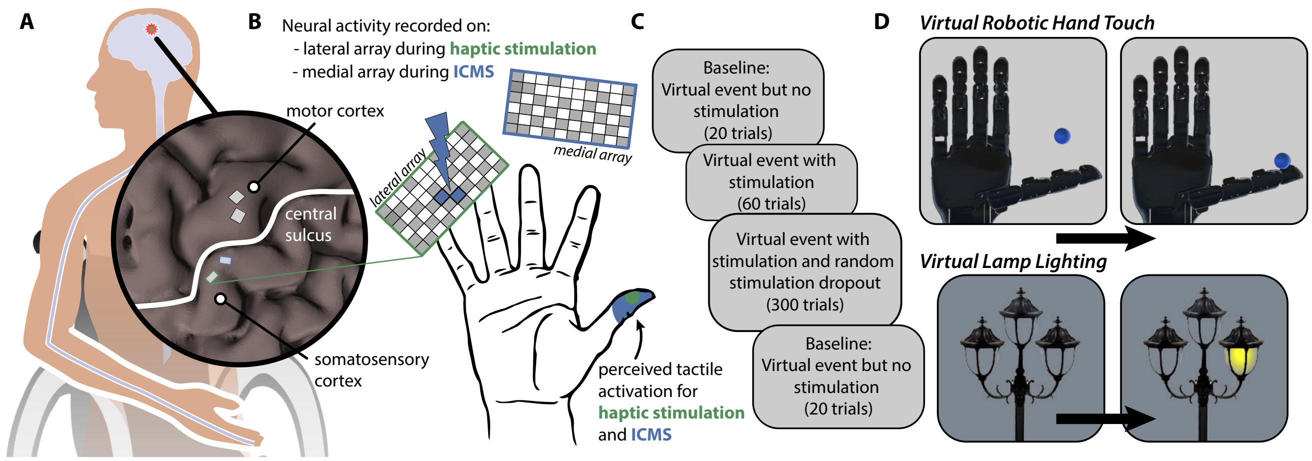

Fig. 1. (A) Microelectrode arrays were implanted in the primary somatosensory and motor cortices of an individual living with spinal cord injury. (B) Intracortical microstimulation (ICMS) on the lateral array in the somatosensory cortex elicited touch perceptions in the thumb while neural activity was recorded on the adjacent, medial array. During haptic stimulation on the thumb, neural activity was recorded from the lateral array due to its overlap with thumb representations [12]. (C) Experimental protocol used for exploring the role of touch inputs from an external virtual system in evoking neural activity. (D) In one scenario an anthropomorphic virtual hand was touched with a virtual sphere. In the other scenario a non-anthropomorphic virtual lamp was illuminated. For each virtual event, tactile stimulation was delivered to the right thumb using either skin vibration (haptic stimulation) or ICMS.

parts of the somatosensory cortex corresponding to the right hand and finger regions [12], [13]. The study was registered as a clinical trial (NCT03161067), was conducted under an Investigational Device Exemption (170010) by the Food and Drug Administration (FDA), and was approved by the FDA, the Johns Hopkins Institutional Review Board, and the U.S. Army Medical Research and Development Command Human Research Protection Office.

B. Experiment

We created a virtual robotic hand (virtual Modular Prosthetic Limb [14]) that, when touched, induced a tactile sensation in the thumb of the participant through either haptic stimulation (i.e., skin vibration) or ICMS (Fig. 1B). We also created a non-anthropomorphic virtual lamp that, when lit, induced a similar tactile sensation (Fig. 1B). The goal of the experiments was to measure evoked neural activity generated by the sensory events in the virtual environments. Further, we aimed to understand how the absence of an expected sensory input influenced the evoked neural response in the somatosensory and motor cortices.

In the first experiment, the participant observed a virtual sphere making contact with the virtual robotic hand. In the second experiment, the participant observed the virtual lamp turning on. For both experiments, the participant first observed 20 virtual event trials (i.e., sphere contact or lamp lighting) without any tactile stimulation to generate the baseline neural activity during the observed virtual events. Next, to establish a link between the tactile sensation and the observed event, the participant underwent an initial training period of 60 trials where they received sensory stimulation as a result of the virtual event. After the initial training, we randomly introduced stimulation dropout trials (i.e. sensory stimulation was not delivered) in approximately one out of every 8-15 trials. In both experiments, sensory stimulation was provided to the right thumb first using skin vibration (haptic stimulation) and then the experiment was repeated with ICMS as the feedback modality. A post-experiment baseline of 20 virtual events with no sensory stimulation was also completed at the end.

Haptic stimulation – which we use here to refer to skin vibration – was delivered using a C3 tactor (Engineering Acoustics Inc) placed on the tip of the right thumb [15]. ICMS was delivered to electrodes in the somatosensory cortex that elicited tactile sensations in the tip of the right thumb using a CereStim (Blackrock Neurotech) [16]. ICMS was delivered using 500 μs biphasic pulses at 100 Hz with an amplitude of 80 μA [13], [15]–[17]. Haptic feedback (i.e., skin vibration) was delivered at 300 Hz and with a magnitude that matched, perceptually, the ICMS intensity as measured using an adaptive two-alternative forced choice psychophysical experiment [15]. It should be noted that the microelectrode array in which these neural activity measurements were taken was different for the two stimulation modalities. This difference in location was due to a technical limitation with the equipment where we were unable to record neural activity from the same microelectrode array in which ICMS was delivered. As a result, the neural recordings from the haptic stimulation experiment overlapped with the right thumb representations in the somatosensory cortex whereas the recordings from the ICMS experiment overlapped more with the middle and ring fingers [12].

For each virtual scene, the participant completed five blocks with 60 virtual events per block, including the stimulation dropout trials, for a total of 300 trials for each stimulation modality. In all conditions, the participant was instructed to use their left hand to press a button as soon as a tactile sensation was perceived during every virtual event trial. They were not told that some trials would lack stimulation and there were no unique visual indications for trials that did not generate a stimulation.

C. Data Analysis

Neural data, the stimulation signal, and button presses were recorded using a Neural Signal Processor (Blackrock

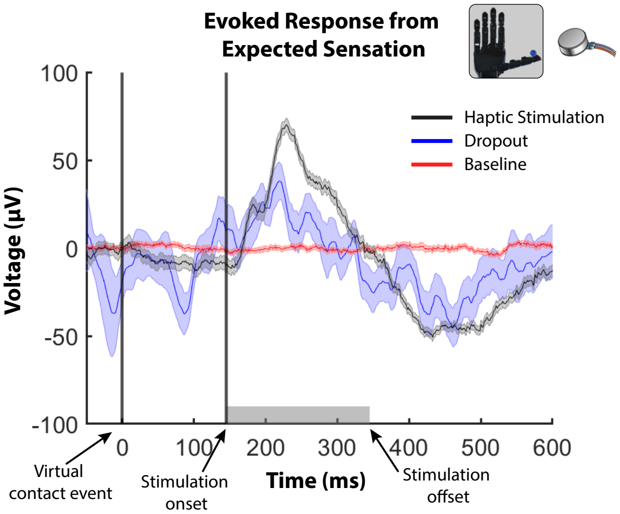

Fig. 2. Average neural response measured by a channel in the somatosensory cortex during a virtual robotic hand being touch by a virtual sphere. Contact in the virtual environment caused a haptic stimulation to the right thumb of the participant. The delay between the virtual contact and stimulation onset was caused by technical issues; however, the evoked response in neural activity occurred as a result of the haptic stimulation. During a random dropout trial (i.e., no haptic stimulation), a sensory-related neural signal was still observed despite the absence of a tactile stimulation. The lack of an evoked response in the baseline condition suggests that the neural response observed is a result of a tactile sensory experience and not the visual observation of the virtual contact event.

Neurotech) with a sampling rate of 2 kHz. Neural activity from the somatosensory cortex was filtered, using a 16 ms sliding window of 256 ms, to extract the spike band power (300-1000 Hz) [18]. Each channel's signal was z-scored and averaged across trials. Shaded error boundaries represent the standard error of the mean. MATLAB was used to perform the analyses.

III. Results & Discussion

We observed strong evoked responses in the somatosensory cortex neural activity during haptic stimulation of the right thumb when the virtual robotic hand was touched by the sphere. Somewhat unexpectedly, we also observed a similar evoked response on the sensory stimulation dropout trials (i.e., the stimulation was randomly removed when the virtual robotic hand was touched) (Fig. 2). The participant reported perceiving a touch sensation in the thumb on 53% of the stimulation dropout trials, despite the absence of tactile stimulation. While the visual observation of the virtual environment heavily influences the perceptual experience, the presence of evoked activity in the somatosensory cortex in regions representing the hand despite no tactile stimulation suggests the expectation of a sensory input caused by the external virtual robotic hand is enough to elicit a neural response. This observation complements previous reports of neural activation localized to regions of the brain representing areas where tactile illusions are perceived, despite no actual touch inputs to those regions [11].

A. Sensory expectation from haptic stimulation

Analyzing the spike band power neural activity [18], we observed a significant response in the somatosensory cortex

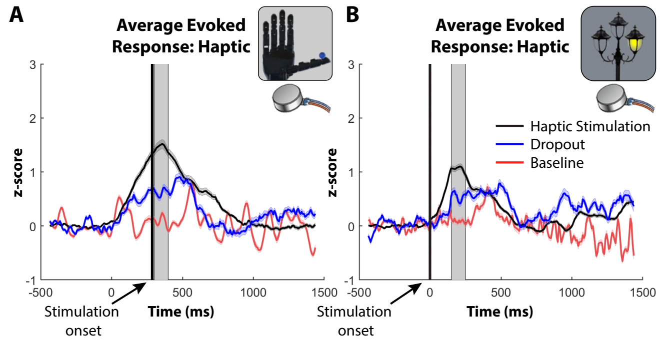

Fig. 3. Expectation of haptic stimulation during the virtual events from both (A) anthropomorphic and (B) non-anthropomorphic systems can elicit neural activity in the somatosensory cortex region representing the site of stimulation. The plots represent the average z-score spike band power activity averaged across all channels in the microelectrode array. Stimulation dropout trials are randomly introduced, but the expectation of a sensory stimulation is enough to evoke a somatosensory response that is significantly greater than baseline levels. The shaded vertical bars represent the time of interest after stimulation.

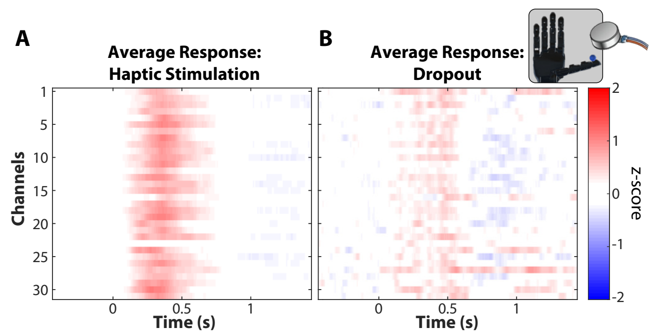

Fig. 4. (A) In the somatosensory cortex lateral microelectrode array, 29 (of 32) channels measured activity during trials with stimulation. (B) During stimulation dropout trials a subset of electrodes also responded, although not as strongly as during actual stimulation trials.

during both stimulation and sensory dropout trials for both the virtual robotic hand touch and the virtual lamp lighting during haptic stimulation experiments (Fig. 3). Within a time of interest (TOI) after stimulation, the evoked activity (mean z-score: 0.62 and 0.54) caused by the expectation of a tactile input, despite its absence, was significantly greater ($p < 0.001$) than baseline (mean z-score: 0.09 and 0.08) for the virtual hand (TOI: 300-400 ms) and virtual lamp (TOI: 150-250 ms) systems, respectively.

Of the two microelectrode arrays in the somatosensory cortex, the results shown here are from the lateral array, which contains more overlap with the right thumb representation in the brain. During the haptic stimulation trials, most of the channels in the array responded during the stimulation period (Fig. 4). Although our current analysis averages the responses from all channels in an array, most, but not all, of the channels exhibited evoked activity during the expectation of tactile perceptions during the dropout trials. In the primary motor cortex, a subset of channels also responded to both the haptic stimulation and dropout trials, suggesting that an expected sensory input engages with more than just the somatosensory cortex.

Although no tactile stimulation was delivered during the dropout trials, the participant still reported as having felt the sensation on many of the dropout trials. This suggests either a

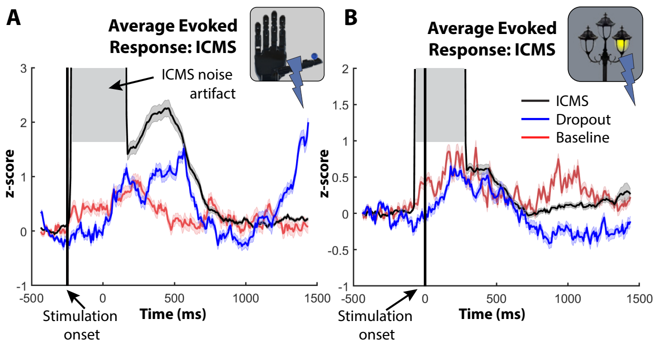

Fig. 5. When delivering ICMS, neural activity in the adjacent medial microelectrode array in the somatosensory cortex also represented evoked responses tied to tactile sensations. (A) During the virtual robotic hand touch experiment, a similar response in the spike band power was observed during dropout trials as compared to trials with actual ICMS delivery. As in, the expectation of an ICMS perception was such that an evoked response could be observed even in the absence of direct cortical stimulation. (B) In the case of the non-anthropomorphic lamp lighting scenario, evoked responses were not clearly distinguishable between the various conditions.

phantom touch perception occurred or a touch sensation was experienced based on expectations formed from the virtual system's behavior during the initial training period. Regardless, these results show that an objective neural marker of an expected touch sensation exists even in the absence of any direct peripheral or cortical stimulation.

B. Sensory expectation from ICMS

During the ICMS experiments with the virtual robotic hand, we also observed a sensory response ($p < 0.001$) in the cortex during random dropout trials (mean z-score: 0.75) compared to baseline (mean z-score: 0.22, TOI: 300-400 ms, Fig. 5). The ICMS delivery resulted in large electrical noise artifacts that prevented identification of neural activity until after the stimulation train had subsided. While we did not observe a difference in neural activity during the non-anthropomorphic experiment dropout trials (mean z-score: 0.37) compared to baseline (mean z-score: 0.36), it is possible that neural activity was modulated in the region of the brain representing the right thumb (i.e., the target of stimulation). However, because we could not record and stimulate through the same array, this neural activity could not be measured while delivering ICMS. It is unclear why the virtual robotic hand scenario elicited an observable cortical response while the virtual lamp did not; however, it could be due to differences in perceived anthropomorphism between the two scenarios and the somatosensory pathways engaged with each system.

Because the neural activity was recorded from a different location for the ICMS condition compared to the haptic stimulation condition, it is difficult to directly compare our observations across the two stimulation modalities; however, there were indications that tactile expectations for both vibration and ICMS could modulate neural activity.

IV. Conclusions

We measured the cortical activity in an individual with chronic microelectrode arrays as a result of sensory stimulation driven by interactions with external systems as a way to identify and better understand how sensory integration may occur. We observed that the somatosensory cortex contains signals representing the expectation of a tactile input being generated by an external system. The presence of neural responses to expected tactile inputs could potentially serve as an objective and physiological measure for probing not only sensorimotor integration but also the overall perceptual experience.

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