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Detailed somatotopy of tongue movement in the human sensorimotor cortex: A case study

1. Introduction

Despite substantial evidence for a representation of body parts in the sensorimotor cortex (SMC) [1], mapping of more detailed motor function in this brain area remains elusive. While some report an orderly somatotopic representation of individual fingers and articulators in the SMC [2,3], others demonstrate that such within-body-parts have overlapping neural representations [4,5], which suggests a lack of discrete organization of within-body-part representations.

Imaging techniques that are typically used to investigate brain function (e.g., fMRI) do not distinguish between critical and non-critical functionality. Observed activity with such techniques can thus represent non-essential involvement such as motor planning or a feedforward/efferent copy. Contrarily, electrical stimulation of the cortex elucidates only areas critical for execution of brain functions and thus allows for studying movement representation in isolation. Here, we applied cortical stimulation on a high-density (HD) electrocorticography (ECoG) electrode grid in a neurosurgical patient to investigate the detailed representation of motor function on the SMC, following ECoG mapping of the tongue.

2. Materials and methods

The patient (male, 28 years-old) suffered from focal seizures with impaired awareness. Seizures were medically refractory and MRI was negative. For epilepsy monitoring purposes and mapping of brain function prior to epilepsy surgery, subdural ECoG grids were implanted for one week, including an HD-grid (64 channels, 3 mm center-to-center electrode distance, 1 mm diameter, Ad-Tech Medical Instrument Corp) over the right ventral SMC. Electrode localization on the cortex (Fig. 1A) was performed using procedures described earlier [6]. Informed consent was signed prior to study participation and consent for sharing footage of the lower part of the face was obtained retrospectively. The study was conducted according to the Declaration of Helsinki (2013).

The patient performed a tongue movement task while ECoG data was recorded from the HD-grid (sampling rate 512 Hz, 22 bits, band-pass filter 0.15–134.4 Hz, Micromed, Italy). The patient was instructed (visually on a computer screen placed at approximately 1 m distance) to move his tongue horizontally inside his mouth, imagine making this movement, or relax during sixteen-second trials. These three conditions were repeated ten times each in random order. Here, we only considered the trials with executed tongue movements and rest trials.

Task-related ECoG data from the HD grid was preprocessed using multiple steps. First, identification of electrodes with noisy or flat channels was carried out by identifying electrodes with deviations in the power-density distribution, line noise values, and raw voltage distributions (identifying the four corner reference electrodes which were facing the dura and which were not used in subsequent analysis steps). Second, a 50 Hz notch filter was applied and data was common average-referenced. Subsequently, high-frequency band (HFB, 65–95 Hz) power was computed per electrode and sample point as described earlier [7]. The HFB power traces were divided into trials, and HFB power per trial was averaged over time for all electrodes. The average HFB responses were compared between executed movement and rest conditions by computing the coefficient of determination (R^2 value) per electrode.

Subsequently, clinical bipolar stimulation was administered (IRES 600 CH electrical stimulator, Micromed, Italy; 1 s trains of 50 Hz, 2 mA, 0.1 ms biphasic square pulses) to twelve electrode pairs (of adjacent electrodes) of the HD grid that showed significantly increased activation during tongue movements as compared to rest. Administered charge density per phase was kept below the safety limit and was similar for all electrode pairs. Stimulation was not administered to the seizure onset location (mesiotemporal, medial temporal gyrus, and posterior temporobasal). Video recordings were made of the patients' face to visually monitor the physical effects of the stimulation, and the patient was asked to verbally report any sensation and/or movement he experienced.

3. Results

Electrodes with significantly increased activity during movement compared to rest ($p < .05$, Bonferroni corrected) were located both anterior and posterior to the central sulcus, with the highest responses occurring more anteriorly (Fig. 1B).

Stimulation of the twelve HD electrode pairs resulted in a tongue movement in one of three directions, or in no movement (Fig. 1C). Notably, electrode pairs that resulted in tongue movement in one direction upon stimulation were only 3 mm removed from electrode pairs that, when stimulated, resulted in tongue movement in another direction (Fig. 1D, Supplementary Video 1).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.brs.2021.01.010

4. Discussion

We show that the ventral sensorimotor cortex contains a representation of different tongue movements at a detailed, millimeter scale. The clearly separated tongue movements that were induced

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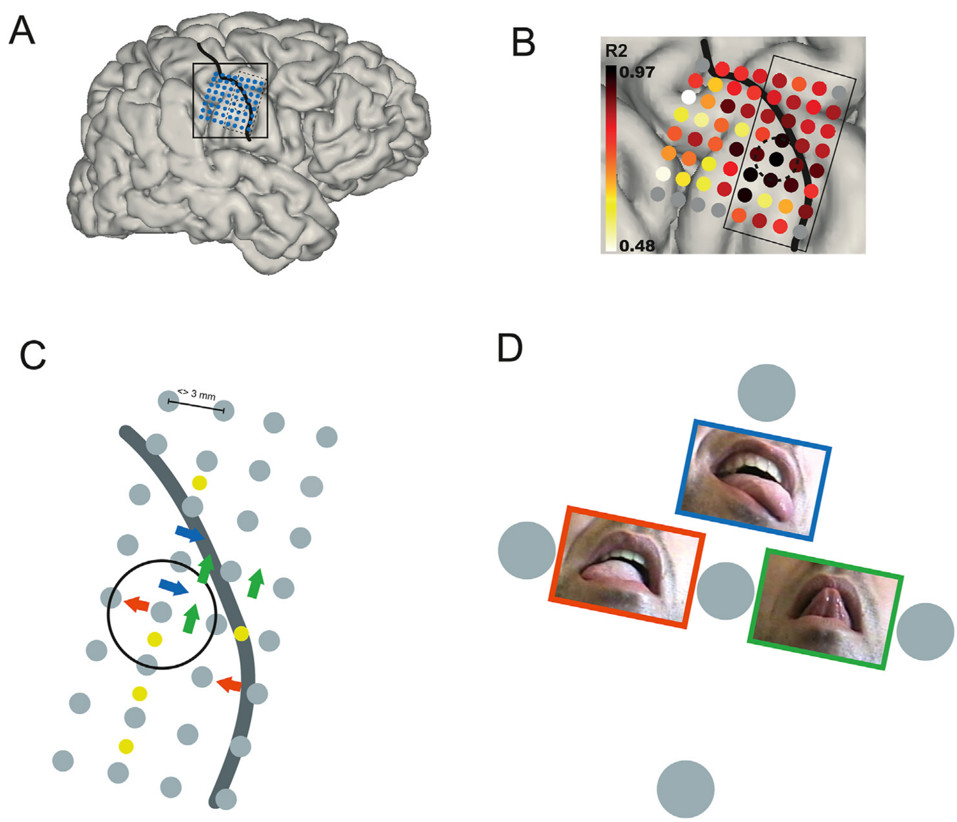

Fig. 1. Visualization of electrodes and neural representations of spontaneous and evoked movements.
Black outlines within subfigures A, B, and C highlight the group of electrodes shown in the consecutive subfigure. A) Visualization of the HD-ECoG grid on the cortex with individual electrodes in blue and the central sulcus in black. B) Visualization of significant HFB power changes related to movement versus rest conditions for the tongue movement task. Electrodes are colored according to their respective R^2 values. Electrodes depicted in grey indicate non-significant R^2 values. C) Visualization of stimulation results. Stimulation locations that did not lead to movement are depicted with yellow dots. Arrows indicate the movement direction (based on the perspective of the observer) of the tongue in the left (red), right (blue), or upwards (green) direction as a response to stimulation over the two electrodes between which the arrow is visualized between which the arrow is locationed D) Visualization of three different tongue movements upon stimulation of three different pairs within a 3-mm radius around the central electrode. Starting position of the tongue was outside of the mouth.

by stimulation of different, but neighboring, electrode pairs suggest that different motor programs of a single body part each have their own representation on the cortex, suggesting such a detailed organization could be found for other body parts as well.

Our findings are in line with previous findings that showed a detailed representation of within-limb movements [2,3] but expose an unexpectedly detailed level of spatially separable representations. This finding contributes new evidence to the long-standing debate about segregation of detailed motor programs in the SMC. Interestingly, electrodes showing a significant response during *voluntary* left-right tongue movements overlapped with, but were more spatially widespread than, electrodes that evoked left-right tongue movements upon stimulation. This observation confirms the notion that measurements of neural representations of voluntary movements unveil more areas than only those representing critical motor processes, while cortical stimulation does succeed in unveiling those critical areas.

During spontaneous movement, we found the highest HFB response anterior in the inferior postcentral gyrus, i.e., on the somatosensory cortex. This is in line with neurosurgical experience, which indicates a less strict separation between motor and sensory function than generally assumed, possibly associated with interindividual variation [1,8].

To our knowledge, our findings represent the first support for the existence of a detailed, distinct mototopy in the tongue area of the sensorimotor cortex. Also, this case study illustrates that cortical mapping with high-density grids is feasible and represents an interesting technique for distinct and detailed localization of motor function, only elucidating areas critical for movement execution at high spatial detail. We propose that further investigation into detailed mapping of within-body-part representations will require spatial specificity in the order of millimeters.

Declaration of competing interest

None.

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