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Research report

Brain encoding of saltatory velocity through a pulsed pneumotactile array in the lower face

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ABSTRACT

Processing dynamic tactile inputs is a primary function of the somatosensory system. Spatial velocity encoding mechanisms by the nervous system are important for skilled movement production and may play a role in recovery of sensorimotor function following neurological insult. Little is known about tactile velocity encoding in mechanosensory trigeminal networks required for speech, suck, mastication, and facial gesture.

High resolution functional magnetic resonance imaging (fMRI) was used to investigate the neural substrates of velocity encoding in the human orofacial somatosensory system during unilateral saltatory pneumotactile stimulation of perioral and buccal hairy skin in 20 neurotypical adults. A custom multichannel, scalable pneumotactile array consisting of 7 TAC-Cells was used to present 5 stimulus conditions: 5 cm/s, 25 cm/s, 65 cm/s, ALL-ON synchronous activation, and ALL-OFF. The spatiotemporal organization of whole-brain blood oxygen level-dependent (BOLD) response was analyzed with general linear modeling (GLM) and fitted response estimates of percent signal change to compare activations associated with each velocity, and the main effect of velocity alone.

Sequential saltatory inputs to the right lower face produced localized BOLD responses in 6 key regions of interest (ROI) including; contralateral precentral and postcentral gyri, and ipsilateral precentral, superior temporal (STG), supramarginal gyri (SMG), and cerebellum. The spatiotemporal organization of the evoked BOLD response was highly dependent on velocity, with the greatest amplitude of BOLD signal change recorded during the 5 cm/s presentation in the contralateral hemisphere. Temporal analysis of BOLD response by velocity indicated rapid adaptation via a scalability of networks processing changing pneumotactile velocity cues.

1. Introduction

Highly evolved plastic mechanisms within the nervous system allow for accurate interpretations of somatosensory flow associated with passive and active touch, and movement. This information is crucial for motor learning, planning, and execution. Loss or impairment of sensory coding networks has a detrimental effect on motor function, while conversely, even partial recovery of these networks can have a beneficial effect on sensorimotor recovery in disease (Hamdy et al., 1998; Kaelin-Lang et al., 2002; Wu et al., 2006).

In tactile velocity coding, the resultant volley of neural activity from direct skin contact is first mediated by primary afferents and their specialized receptor terminals located in various levels of the dermis in glabrous and hairy skin. These specialized Aβ mechanoreceptors, are either unencapsulated or encapsulated, and are tuned to encode select characteristics of incoming stimuli based on their neural adaptation properties (fast adapting vs slow adapting), receptive field size, best frequency, and absolute threshold sensitivity to mechanical input (Edin et al., 1995; Essick, 1998; Bensmaia, 2008; McGlone and Reilly, 2010). At higher levels in the

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nervous system, the encoding of moving tactile stimulation appears to involve a decomposition of the mostly isomorphic representation of the stimulus at the periphery, into a complex signal of direction and velocity contours that are managed throughout progressive neural circuits (Jones, 1992; Ferezou et al., 2007). Signal refinement is the result of an adaptive relay of competitively filtered neuronal signals throughout select regions of somatosensory and sensorimotor networks. In human limb studies, these regions can include primary somatosensory (postcentral; SI, subareas BA 3a, 3b, 1, 2), secondary somatosensory (SII, BA 40, 43), primary motor (precentral; MI, BA 4), supplemental motor (SMA, BA 6), posterior parietal (PPC, BA 7), prefrontal, and insular cortices, as well as sensorimotor integration regions in the superior temporal gyrus (STG), supramarginal gyrus (SMG), thalamus, and cerebellum (Blatow et al., 2007; Strick et al., 2009; Hu et al., 2012; Huang et al., 2012; Zembrzycki et al., 2013; Schnepel et al., 2014; Rocchi et al., 2016; Jiang et al., 2016).

The perioral region is dominated by slowly adapting (Merkel cell neurites, Ruffini corpuscles) mechanoreceptors, with smaller populations of rapidly adapting (Meissner corpuscles) Aβ mechanoreceptors, but lacks the classic U-function sensitivity assigned to the Pacinian corpuscle (PC) (Barlow, 1987; Johansson et al., 1988; Nordin and Hagbarth, 1989). This is consistent with histological and physiological studies which have not found PC receptors in facial skin (Dubner et al., 1978; Halata and Munger, 1983; Munger and Halata, 1983). Mechanosensory projections from the V2 and V3 divisions of the trigeminal nerve complex are somatotopically mapped in the chief sensory nucleus of V, ventroposteromedial nucleus of the thalamus (VPm), cerebellum, and multiple cortical maps in face S1 and S2 (Welker, 1987; DaSilva et al., 2002; Mottolese et al., 2013). Precise, feedback-dependent orofacial movements, including speech, suck, mastication, and gesture benefit from adaptive neural networks that respond rapidly to facial somatosensory (proprioceptive, tactile) signals resulting from bilabial contact and opening, changes in intraoral air pressure, and conformational changes in perioral skin associated with jaw motion and perioral stretch (Barlow and Bradford, 1996; Barlow, 1998; Capra and Dessem, 1992; Trulsson and Johansson, 2002; Estep and Barlow, 2007; Tomita et al., 2012).

In many research paradigms, stimulation of the facial region in neuroimaging environments has proven to be technically challenging. Standard electromechanical- and piezoceramic/piezoelectric-based stimulating devices require feed wires and large source currents to function, both of which can interfere with MR signal acquisition, or become heated by radiofrequency pulses if not properly shielded (Blankenburg et al., 2003; Antal et al., 2014; Lipworth et al., 2015). Similarly, some pneumatic stimulators involve complex set-ups, and are not easily adapted to applications that include participants with neurological disease, or time-restricted imaging paradigms (Servos et al., 1999; Briggs et al., 2004; Huang et al., 2012, Dresel et al., 2008). The pneumotactile stimulator in the present study (GALILEO Somatosensory™) uses a chambered tactile cell (TAC-Cell) which can be applied quickly to the skin of any population using double adhesive tape collars, with scalable and programmable control to create saltatory tactile arrays unique to study designs. Recent studies utilizing pulse trains of pneumotactile stimulation at different stimulus rates (2–6 Hz) with just a single TAC-Cell placed on either the glabrous hand or lower face have shown significant and unique short- and long-term adaptation patterns in S1, S2, and posterior parietal cortex (PPC) using magnetoencephalography source localization methods (Popescu et al., 2010, 2013; Venkatesan et al., 2010, 2014), and electroencephalography (Custead et al., 2015).

The aim of the present study is to extend our previous work from single channel TAC-Cell stimulation at a single skin location, to a multichannel TAC-Cell array to map the brain's evoked fMRI BOLD network in response to dynamically patterned spatial arrays programmed to generate saltation velocities over the perioral and buccal surface of the lower face. Additionally, we extend our research paradigm by utilizing high-resolution fMRI to; (1) include neurovascular coupling links to peripheral stimulation (2) improve spatial resolution that may be combined with high temporal resolution EEG/MEG in next-step projects, and (3) begin to explore regions of activity that are involved in whole brain (cortical and deeper subcortical) network activation. We hypothesize that a putative neural 'somatosensory velocity network' with key ROIs in both somatosensory and relevant motor areas of the brain will emerge which scale their hemodynamic response (%BOLD change) as a function of saltatory velocity.

2. Results

2.1. Main effect of velocity

Pneumotactile velocity stimuli delivered to the non-glabrous skin of the right lower face produced BOLD activation in multiple regions of bilateral cortex and cerebellum (Table 1). Statistical parametric mapping (GLM) of the main effect of velocity is shown in Fig. 1 (second level, one-way ANOVA within-subjects, $F(2,38) = 11.85$, $p < 0.001$, uncorrected, minimum extent 10 voxels), with

Table 1
Main Effect of Saltatory Pneumotactile Velocity Stimulation. Whole brain results (second level group analysis of 20 participants, one-way ANOVA within-subjects design). Data represents all 3 velocities (5, 25, 65 cm/s) inserted into analysis matrix. The 6 significant activation clusters used for region of interest (ROI) analysis of putative facial sensorimotor velocity processing networks are highlighted (*). Note: Both L precentral and postcentral gyri comprise cluster '2686,' and both R superior temporal and R supramarginal gyri comprise cluster '585.'

Main Effect of Velocity				MNI Coordinates		
Region	Laterality (re: stimulus)	Extent (k = mm^3)	F-score	x	y	z
L Precentral Gyrus*	Contra	2686	37.81	−57	3	40
L Postcentral Gyrus*	Contra		35.37	−49.5	−24.5	25
R Superior Temporal Gyrus*	Ipsi	585	26.57	51	−32	20
R Supramarginal Gyrus*	Ipsi		15.66	68	−22	22.5
R Cerebellum (VI)*	Ipsi	144	24.78	26	−57	−23
R Inferior Frontal Gyrus	Ipsi	236	23.53	58	6	30
R Precentral Gyrus*	Ipsi		17.11	50.5	0.5	52.5
L Posterior-Medial Frontal	Contra	264	21.33	−7	−2	63
L Middle Occipital Gyrus	Contra	244	20.84	−35	−90	23
L Cerebellum (VI)	Contra	75	14.42	−22	−60	−25
R Middle Occipital Gyrus	Ipsi	26	11.28	41	−87	13
R Inferior Occipital Gyrus	Ipsi	24	10.38	38	−72	−3
R Rolandic Operculum	Ipsi	5	9.21	46	−5	13