

Sequences of cortical activation for tactile pattern discrimination using magnetoencephalography

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To observe sequential stages in tactile pattern discrimination and their modification with and without attention, we used whole-head anatomically constrained magnetoencephalography to spatiotemporally map brain responses. Eight, normal, right-handed participants discriminated between two patterns presented on the palm. Latencies of neural activity were determined from stimulus contact with the palm. Early cortical activation moved from sensorimotor cortex (SM1) to secondary somatosensory cortex (SII), Broca's area (BA), and superior parietal cortex by 65 ms. It continued bilaterally to temporal and frontal poles by 290 ms. Subtraction of nonattended from attended conditions removed primarily the early contralateral sensory components. There was some indication of a preferred order of sensory processing that may express and optimize hemispheric computational

specializations. Results indicate similar functional organizations for tactile and visual pattern recognition. *NeuroReport* 20:941–945 © 2009 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

The order and timing of activation of cortical areas used in analyzing sensory information are crucial for the understanding of cortical dynamics. Most researches have focused on the visual cognition and the activation of visual cortical areas. In the visual system, hierarchical and parallel operations coexist [1]. A ventral-processing stream has been identified for analyzing the visual scene into form, color, and features [2]. Anatomically, the ventral stream connects striate, prestriate, and inferior temporal brain regions. However, relatively few researchers have examined somatosensory cognition and the activation of somatosensory cortical areas. We investigated the spatiotemporal sequence of activation for tactile pattern (TP) recognition and whether it proceeded in a sequential hierarchical manner, similar to vision.

Earlier whole-head magnetoencephalography (MEG) research has shown that for visual presentations, there is a ventral pathway with activation onsets sequentially engaging V1, other retinotopic cortices, occipitotemporal areas involved in midlevel vision (e.g. perceptual grouping), posterior temporal areas performing material-selective encoding (e.g. for words and faces), and anterior temporal and posterior prefrontal regions thought to perform semantic and other higher processes [3,4]. Visual information seems to travel from modality-specific to

modality-general regions. We examined whether the somatosensory system has an analogous organization. Although some research suggests that tactile information is processed by the visual system [5,6], other research supports an initial somatosensory-specific processing stream [7–9].

No study to date has investigated the cortical dynamics among these neural regions involved in TP perception. Given the difficulty of synchronizing tactile stimulus presentation with the neural recording in MEG, little is known about the time course of TP recognition. Whole-head MEG can localize differential somatosensory activity within somatosensory cortical regions, and also can localize differences in the timing of activation in these brain areas. It has been shown that MEG can display the organization of S1 [10], and that attention can modulate the MEG signal during somatosensory cognition in frontal and parietal regions [11].

Using whole-head MEG, we examined TP discrimination in neurologically intact individuals. We compared spatiotemporal patterns of cortical activity for attended and nonattended TP discrimination to determine activation associated with pattern identification separate from sensory inputs. Anatomically constrained dynamic statistical maps (brain movies) were created to indicate the location and time course of the neural activation. If the

somatosensory system has an independent but hierarchical organization similar to that of the visual system, activation should begin in modality-specific tactile regions and then move to modality-general portions of the ventral object-processing stream.

Methods

Participants

Eight right-handed men (18–30 years of age) participated after providing informed consent. None had a history of mental or physical illness, head injuries, or drug abuse. Ethical approval was received from the Universities of Utah and Denver. The participants' data were screened for MEG artifacts; two participants were eliminated from the analyses because of recording artifacts and data corruption.

Stimuli

A custom-made pneumatic tactile stimulator delivered precise, controlled stimulation to the palm. It was constructed from two pieces of Plexiglas into which holes and divots had been drilled. They were screwed together to form output holes for the air and internal bladders to direct the air to the holes. Thin rubber was glued over the output holes so that air puffs extended the rubber membrane to touch the skin. Rubber tubes conducted compressed air input (100 psi) to the stimulator to produce stimulation. Air input was controlled by a solenoid box outside the shielded room. Solenoids determined the tubes that received the air. The stimulator was driven by a computer and delivered time-locked stimulation with millisecond precision using STIM (Biolink, UK). Two discriminable patterns with equal stimulation points ('X' and '+') were selected after pilot testing.

Procedure

In a 1-h session, the participants performed two tasks that differed in the cognitive activity rather than the degree of sensory stimulation: (i) TP discrimination (TP) the participants distinguished pattern-1 from pattern-2, and (ii) ignore TP (TP_{ignore}) – the participants received the patterns but ignored them while listening to a story from which they answered questions. The participants were given practice to reach criterion performance; this eliminated learning during experimental trials. To measure performance accuracy, the participants indicated when pattern-1 occurred by raising the index finger of the nonstimulated hand, breaking an optical circuit. Stimuli had a stimulus onset asynchrony of 2 s. The patterns were randomly presented for 300 trials. Every minute, the participants were given 'blink' breaks. Each task was performed on left and right hands.

Data processing

MEG signals were recorded from 204 channels at 0.1–100 Hz using a Neuromag Vectorview instrument

(Elekta, Stockholm, Sweden) with orthogonal pairs of planer gradiometers at 102 locations over the entire scalp. Individual averages were constructed for each task for each participant after rejecting trials with eye blinks or other artifacts using amplitude criteria confirmed by visual inspection. Head movement was minimized using a chin strap, foam padding on the head, and bite bars.

Cortical surface reconstructions

For each participant, geometrical representations for the cortical surfaces were obtained [12–14]. To average signals across the participants, the reconstructed surface for each participant was morphed into an average spherical representation, optimally aligning the sulcal and gyral features across the participants but minimizing metric distortions [14].

Forward solution

To calculate the signal expected at each MEG sensor for each dipole, a boundary element method was used [15,16]. The MRI coordinate system was aligned with the MEG sensor coordinate system using three head position (HPI) coils attached to the scalp. The position of the HPI coils with respect to the participant's head and MRI was determined by measuring multiple points using a Polhemus FastTrack 3D digitizer (Polhemus, Colchester, Vermont, USA).

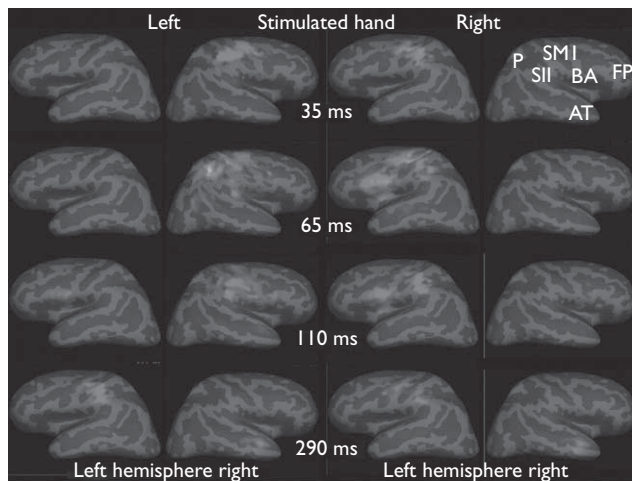
Inverse solution

Time courses of cortical activity were estimated using a noise-normalized, anatomically constrained, linear estimation approach [12]. No a priori assumptions were made about local dipole orientation, and thus, three components were required for each location. A sensitivity-normalized estimate of the local current dipole power was calculated for each location [12,17]. For TP and $TP - TP_{\text{ignore}}$ analyses, significance thresholds for the dynamic statistical parameter maps (dSPMs) were set at a P value less than 10^{-8} , with a full red response indicating a P value less than 10^{-11} and a P value less than 10^{-17} indicating peak activation with a bright yellow color. Noise sensitivity-normalized cortical surface-constrained minimum norm inverse solutions were calculated every 5 ms for each condition and each participant. These movies were averaged on the cortical surface across the participants, after aligning their sulcal–gyral patterns. To account for the lag between stimulus trigger and stimulus presentation created by air flow through the tubes, 40 ms from reported activation times was subtracted.

Results

Pattern discrimination (Fig. 1)

Tps delivered to left and right hands produced similar mirror-image early cortical processing patterns. An initial contralateral MEG signal in the S1 hand area was observed by 25 ms, and it became robust by 35 ms. This unilateral activation spread laterally to the sensorimotor

Fig. 1

Tactile pattern discrimination activation sequence for the left and right hands. Statistical activation maps are overlaid on inflated brains (i.e. cortical tissue in the sulci is expanded and represented on the surface with the gyri; dark grey indicates gyri and light grey indicates sulci) from lateral views. Early cortical activation (35 ms) begins in the contralateral sensorimotor cortex (SM1) and is primarily determined by the hand stimulated. By 65 ms, contralateral activation spreads to Broca's area (BA) and BA homologue, secondary somatosensory cortex (SII), and parietal cortex (P). By 150 ms, activation was observed in both hemispheres and ended in anterior temporal (AT) and frontal (F3/FP) regions by 290 ms.

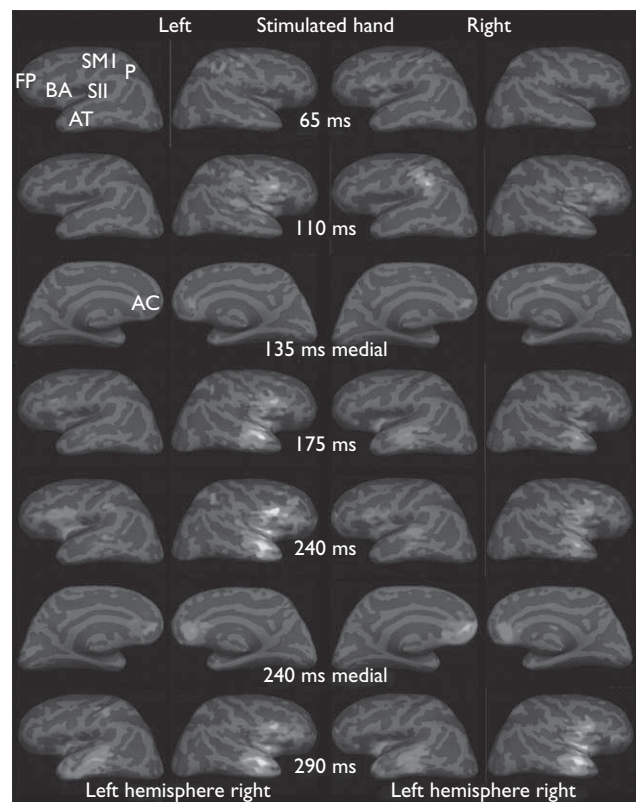
cortex (SM1), including the pre-central gyrus and post-central gyrus, which is consistent with bidirectional neuronal connections between these areas [18]. Between 65 and 110 ms, activation spread to the secondary somatosensory cortex (SII), the parietal cortex, and the inferior frontal gyrus [Broca's area (BA) and BA homologue, a region homologous with BA on the right side] within the contralateral cortex.

At 65 ms, the cortical activation sequence differed depending on the hand stimulated, suggesting a hand-by-hemisphere interaction. For left-hand conditions, peak activation was observed in the contralateral (right hemisphere, RH) parietal cortex, in addition to the continued activation of the right (contralateral) SM1. By 110 ms, activation was also found in BA and BA homologue. For right-hand conditions, peak activation at 65 ms was found in contralateral SM1 (left hemisphere, LH) and BA; activity was also observed in the contralateral operculum/insula, an area ventral to contralateral SII, and contralateral SM1. By 110 ms, activation increased in left contralateral parietal cortex. This apparent reversal in the sequence of activation of BA/BA homologue and parietal cortex for the different hand conditions is an intriguing result, but future research with increased statistical power will be required to determine its robustness and reliability.

By 290 ms, cortical activation patterns had become similar in both area and laterality, regardless of which hand was stimulated: SM1 activation and ventral temporal lobe activation was observed in the LH, and anterior temporal (AT) activation was observed in the RH. Overall, results showed a sequence of activation consistent with what would be expected from an organization of the somatosensory system similar to that of the visual system. Initially, tactile information seems to be processed unilaterally in modality-specific cortical regions specialized for perceptual processing. It is then processed bilaterally in modality-general temporal areas to permit pattern recognition.

Attention effects (Fig. 2)

To isolate the more cognitive components of TP discrimination, dSPMs were calculated from the MEG

Fig. 2

Attentional effects of tactile pattern (TP) discrimination activation sequence for left and right hands when sensory inputs were subtracted (i.e. $TP - TP_{\text{ignore}}$). With the exception of the initial sensorimotor cortex (SM1) activation, the pattern of activation followed a similar course as for TP. At 65 ms, left-hand stimuli produced relatively stronger activation in contralateral parietal cortex (P) and right-hand stimuli produced relatively stronger activation in contralateral Broca's area (BA). By 110 ms, activation for left-hand stimuli moved to contralateral BA homologue and activation for the right-hand stimuli moved to contralateral P and to BA homologue. At 135 ms, the anterior cingulate (AC) also indicated a hand by hemisphere interaction. Hand-independent bilateral activation in the insula/BA and anterior temporal (AT) began at 175 ms and continued to 290 ms where it ended in AT and frontal pole (FP) regions.

waveforms obtained by subtracting TP_{ignore} from TP waveforms. This analysis removed the initial sensory response common to both conditions.

For both hand conditions, $TP - TP_{\text{ignore}}$ removed SM1 activation at 35 ms. The activation maps showed the first attention effects in the contralateral hemisphere at 65 ms, and showed the interaction between hemisphere and hand described above. For left-hand subtractions, the main attention-related differential activity at 65 ms was observed in the right parietal cortex; by 110 ms, the activity moved to the right BA homologue, insula/SII, and superior temporal regions. For right-hand subtractions, differential activity was observed at 65 ms in BA (LH). By 100 ms, activity moved to the left parietal cortex, right BA homologue, and superior temporal regions.

At 175 ms, the activation patterns were again similar for both subtraction conditions. By 240 ms, activation was observed in bilateral AT, insula, and BA, and ended at 290 ms in the frontal and temporal poles (F3/FP, AT; see lateral and medial views in Fig. 2). This pattern of activation is consistent with that observed during visual pattern recognition [3,4].

The subtractions also showed attention-related activity in the anterior cingulate (AC; medial views in Fig. 2). Right-hand conditions showed contralateral (LH) AC activation at 110 ms, but left-hand conditions did not show contralateral, (RH) AC activation until 135 ms. This suggests that AC activation is modulated by attention and by hand and hemisphere. For both conditions, bilateral AC activation was observed at 240 ms. These results correspond with findings from functional MRI (fMRI) studies of tactile object recognition with real objects [8,9].

Discussion

This study is the first to use whole-head MEG to examine spatiotemporal maps of brain activity for TP discrimination and their modification with attention. The results support a ventrolateral TP-processing stream that involves similar neural regions shown in fMRI research on tactile object recognition [8,9]. The ventrolateral somatosensory pathway includes SI, SII areas (including the posterior insula and retroinsular cortex), the inferior parietal cortex, and the motor cingulate. As predicted, TP information moved from modality-specific to modality-general regions: activity followed a progression beginning in SM1, moving to SII areas, and then on to the ventral temporal cortex. This activation is somatosensory-specific, because primary visual areas were not activated and the early activation patterns differed from those evoked by visual stimuli using the same MEG methodology [3,4]. Thus, the results provide evidence for a modality-specific ventrolateral pathway for TP recognition.

Like vision, the final stages of TP recognition seem to be bilateral and to activate modality-general cortical regions. Touch and vision produce similar late activation patterns for complex stimuli [4]. In all cases, activation ends in AT and F3/FP. The similarity of the ventrottemporal activation suggests that these regions have transmodal functions in complex pattern recognition. This is a striking confirmation of multimodal convergence.

Using the visual system as a reference, the results support a general framework for the interpretation of activation during TP processing. On the basis of the known neurophysiological and anatomical constraints of the cortical somatosensory system, this framework parallels primary somatosensory cortex (SI) with striate cortex, area 5 with posterior modality-specific visual association cortex, and area 7 either with more anterior visual association cortices or an area of overlap between somatosensory and visual systems [19]. Other areas implicated in higher-level somatosensory processing include the inferior parietal cortex, the posterior insula, and the retroinsular cortex. These regions may have analogues with object-encoding regions within the ventral visual stream. Ultimately, all sensory systems may converge on polymodal regions in temporal cortex and limbic areas [20,21]. This ventrolateral pathway model implies that in humans, somatosensory inputs are processed hierarchically from S1, to the SII complex, to the ventral temporal lobe, and to the hippocampus. Patient and neuroimaging studies confirm the relevance of this ventrolateral object-recognition pathway for touch [7–9,19]. In a PET study of tactile memory-processing, researchers compared activation produced by a tactile memory task with that of exploratory movements and pure sensory processing. Results corresponded to a ventrally directed parieto-insular pathway, including the posteroventral insula and perirhinal cortex in which long-term representations of tactual experiences are formed [22]. Functional MRI studies point to the importance of S1, SII, the superior parietal cortex, the inferior frontal gyrus (Broca's area and its RH homologue), and the lateral occipital cortex and temporal regions for TP recognition [8,9,23,24].

Notably, activation patterns also suggest a potential processing difference in the sequence of neural activation in the two hemispheres depending on the hand stimulated. Although common regions were activated overall for the two hand conditions, the activation sequence seemed to be specific to each. Right-hand pattern discrimination produced initial contralateral (LH) activation moving from SM1 to SII to BA, and then to the parietal cortex. Activation continued bilaterally along the ventral temporal object-processing stream to end in AT and FP. Left-hand pattern discrimination activated the contralateral (RH) SI and SII areas, but

activation moved to the parietal cortex and then to BA homologue before continuing bilaterally to AT and FP. The sequence of modality-specific activation for unilateral stages of TP processing may be specific to each hemisphere. The hemispheres may differ in the prioritization of neural processing used to integrate stimuli: TPs may be preferentially processed initially in the RH as spatial information [25] but they may be preferentially processed in the LH as a temporal sequences. This is an initial study and further research is needed to address this issue.

Conclusion

MEG during TP recognition confirms the regions implicated by some fMRI studies and shows their progression from primary somatosensory to parietal, temporal, and frontal cortices. This sequence parallels the ventral visual object-processing stream, and the tactile sequence terminates in the same supramodal areas as the visual stream. Furthermore, these novel MEG results confirmed the activation of frontal and temporal poles for pattern recognition, often missed out in fMRI experiments. Additional researches are needed to explore the relationship between the sequence of processing and hemispheric specialization.

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References

- De Yoe EA, Van Essen DC. Concurrent processing streams in monkey visual cortex. *Trends Neurosci* 1988; **11**:219–226.
- Ungerleider LG, Mishkin M. Two cortical visual systems. In: Ingle DJ, Goodale MA, Mansfield RJW, editors. *Analysis of visual behavior*. Cambridge, Massachusetts: MIT Press. pp. 549–586.
- Halgren E, Mendola J, Chong CD, Dale AM. Cortical activation to illusory shapes as measured with magnetoencephalography. *Neuroimage* 2003; **18**:1001–1009.
- Marinkovic K, Dhond RP, Dale AM, Glessner M, Carr V, Halgren E. Spatiotemporal dynamics of modality-specific and supramodal word processing. *Neuron* 2003; **38**:487–497.
- Deibert E, Kraut M, Kremen S, Hart J. Neural pathways in tactile object recognition. *Neurology* 1999; **52**:1413–1417.
- Sathian K, Zangaladze A, Hoffman JM, Grafton ST. Feeling with the mind's eye. *Neuroreport* 1997; **8**:3877–3881.
- Reed CL, Caselli RJ, Farah MJ. Tactile agnosia, underlying impairment and implications for normal tactile object recognition. *Brain* 1996; **119**:875–888.
- Reed CL, Halgren E, Shoham S. The neural substrates of tactile object recognition, an fMRI study. *Hum Brain Mapp* 2004; **21**:236–246.
- Reed CL, Klatzky R, Halgren E. What versus where for haptic object recognition, an fMRI study. *Neuroimage* 2005; **25**:718–726.
- Suk J, Ribary U, Cappell J, Yamamoto T, Llinas R. Anatomical localization revealed by MEG recordings of the human somatosensory system. *Electroencephalogr Clin Neurophysiol* 1991; **78**:185–196.
- Mauguiere F, Merlet I, Forss N, Vanni S, Jousmaki V, Adeleine P, Hari R. Activation of a distributed somatosensory cortical network in the human brain, a dipole modelling study of magnetic fields evoked by median nerve stimulation. Part II, Effects of stimulus rate, attention and stimulus detection. *Electroencephalogr Clin Neurophysiol* 1997; **104**:290–295.
- Dale AM, Sereno MI. Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction, a linear approach. *J Cogn Neurosci* 1993; **5**:162–176.
- Dale AM, Fischl BR, Sereno MI. Cortical Surface-Based Analysis I, Segmentation and Surface Reconstruction. *Neuroimage* 1999; **9**:179–194.
- Fischl B, Sereno MI, Tootell RB, Dale AM. High-resolution intersubject averaging and a coordinate system for the cortical surface. *Hum Brain Mapp* 1999; **8**:272–284.
- De Munck JC. A linear discretization of the volume conductor boundary integral equation using analytically integrated elements. *IEEE Trans Biomed Eng* 1992; **39**:986–990.
- Oostendorp TF, Van Oosterom A. Source parameter estimation in inhomogenous volume conductors of arbitrary shape. *IEEE Trans Biomed Eng* 1989; **36**:382–391.
- Dale AM, Liu AK, Fischl BR, Buckner RL, Belliveau JW, Lewine JD, Halgren E. Dynamic statistical parametric mapping, combining fMRI and MEG for high-resolution imaging of cortical activity. *Neuron* 2000; **26**:55–67.
- Jones EG, Powell TP. An anatomical study of converging sensory pathways within the cerebral cortex of the monkey. *Brain* 1970; **93**:793–820.
- Caselli RJ. Ventrolateral and dorsomedial somatosensory association cortex damage produces distinct somesthetic syndromes in humans. *Neurology* 1993; **43**:762–771.
- Friedman DP, Murray EA, O'Neill JB, Mishkin M. Cortical connections of the somatosensory fields of the lateral sulcus of macaques: evidence of a corticolimbic pathway for touch. *J Comp Neurol* 1986; **252**:323–347.
- Mishkin M. Analogous neural models for tactual and visual learning. *Neuropsychologia* 1979; **17**:139–150.
- Bonda E, Petrides M, Evans A. Neural systems for tactual memories. *J Neurophysiol* 1979; **75**:1730–1737.
- Amedi A, Jacobson G, Hendler T, Malach R, Zohary E. Convergence of visual and tactile shape processing in the human lateral occipital complex. *Cereb Cortex* 2002; **12**:1202–1212.
- James TW, Humphrey GK, Gati JS, Servos P, Menon RS, Goodale MA. Haptic study of three-dimensional objects activates extrastriate visual areas. *Neuropsychologia* 2002; **40**:1706–1714.
- Banich M. *Cognitive neuroscience and neuropsychology*. 2nd ed. New York: Houghton Mifflin Company.