Differential Effects of Cognitive Demand on Human Cortical Activation Associated With Vibrotactile Stimulation

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1Department of Psychology and 2Department of Neurology and Neurosurgery, McGill University; and 3Groupe de recherche sur le système nerveux central, 4Département de physiologie, and 5Département de stomatologie, Université de Montréal, Montreal, Quebec, Canada

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Albanese M-C, Duerden EG, Bohotin V, Rainville P, Duncan GH. Differential effects of cognitive demand on human cortical activation associated with vibrotactile stimulation. J Neurophysiol 102: 1623–1631, 2009. First published June 24, 2009; doi:10.1152/jn.91295.2008. This event-related functional MRI study examines the neural correlates of vibrotactile sensation within the context of different psychophysical demands. Nine subjects received vibrotactile stimuli on the right volar forearm during detection, localization, and passive tasks. In the detection task, subjects indicated the offset (end) of each stimulus by pressing a response key with their left hand. In the localization task, subjects identified the location of the stimulus (“distal?” or “proximal?”) by pressing the appropriate response key 4 s after the end of the stimulus. In the passive task, subjects received the same vibrotactile stimuli, but no response was required. Analysis of stimulus-evoked activity compared with the resting baseline period revealed significant bilateral secondary somatosensory cortex activation for all three tasks. However, only in the offset-detection and localization tasks was stimulus-evoked activation observed in other expected areas of tactile processing, such as contralateral primary somatosensory cortex neighboring the posterior parietal cortex (SI/PPC) and in bilateral anterior insular cortex (aIC). During the localization task, we identified vibrotactile-evoked activation in the right aIC, which was maintained after the termination of the stimulus. Results suggest that vibrotactile-related activation within SI/PPC and aIC is enhanced by the increased levels of attention and cognitive demands required by the detection and localization tasks. Activation of aIC not only during vibrotactile stimulation, but also during the poststimulus delay in the localization trials, is consistent with the growing literature linking this area with the perception and short-term memory of tactile information.

INTRODUCTION

Brain imaging studies of innocuous tactile stimulation in humans have reported activation in a number of areas, including the primary and secondary somatosensory cortices (SI and SII) and posterior parietal cortex (PPC) (Bonhomme et al. 2001; Burton and Sinclair 2000b; Burton et al. 2004, 2008a; Disbrow et al. 1998; Francis et al. 2000; Gelnar et al. 1999; Golaszewski et al. 2006; Kostopoulos et al. 2007; McGlone et al. 2002; Soros et al. 2007). In addition, the posterior insular cortex has also been implicated in tactile perception (Burton et al. 1993; Davis et al. 1998; Francis et al. 2000; Golaszewski et al. 2006; McGlone et al. 2002; Soros et al. 2007), as opposed to the anterior insula cortex (aIC), where activation is usually associated with the perception of noxious stimuli (Apkarian et al. 2005). However, increasing evidence suggests a more general involvement of the aIC in the perception of innocuous somatosensory stimuli such as vibration (Burton et al. 1993; Soros et al. 2007) and touch (Blakemore et al. 2005; Olausson et al. 2002).

Some previous studies have suggested that somatosensory-related activation levels within parietal areas (and potentially the insula) may be modulated by the context within which the tactile stimuli are delivered (Burton et al. 1999; Johansen-Berg et al. 2000). For example, vibrotactile stimuli presented during an active frequency-discrimination task were associated with enhanced activity in contralateral SI, compared with that elicited by passive vibrotactile input (Staines et al. 2002). The right aIC is also influenced by relevant sensory information and has been suggested to be part of a right-lateralized cortical network mediating attention to innocuous sensory events (Downar et al. 2000, 2002).

In spite of these studies showing enhanced cerebral sensory activity during active tasks, the majority of human imaging studies assessing vibrotactile processing during the past decade have used only the passive presentation of stimuli (Bonhomme et al. 2001; Francis et al. 2000; McGlone et al. 2002; Siedentopf et al. 2008); those studies that engaged the subjects in the performance of active tasks have concentrated on the discrimination of vibratory frequency (Burton et al. 2008a,b; Li et al. 2007; Staines et al. 2002), duration (Burton et al. 2008a,b), or intensity (amplitude) (Nelson et al. 2004a,b), rather than the spatial features of the stimulation, which might be more specifically processed in parietal areas. The potential importance of studying in greater detail the influences of attention on sensory activation within the cortex has been recently underscored by reports indicating that active engagement in discrimination tasks may play an important role in inducing neuroplastic changes within somatosensory areas (Recanzone et al. 1992). An improved understanding of the role of attentional modulation in shaping cortical sensory activation may have far-reaching implications in rehabilitating patients who suffer the consequences of peripheral deafferentation and the resulting maladaptive changes in the organization and responsiveness of somatosensory areas of the cortex, such as that described in phantom-limb pain (Flor et al. 2006).

Therefore the purpose of the present functional magnetic resonance imaging (fMRI) study was to examine the cerebral correlates of vibrotactile sensation associated with the localization of the stimulus, compared not only with another active psychophysical task (detection of stimulus offset), but also with the passive presentation of stimuli. We hypothesized that...
the activation of parietal (contralateral SI and bilateral SII) and bilateral insular cortices by vibrotactile stimuli is influenced by both the level of attention toward those stimuli and the specific demands of different psychophysical tasks. These five regions of interest were chosen based on previous literature implicating their involvement in processing vibrotactile stimuli (Nelson et al. 2004a; Soros et al. 2007). Portions of these data were previously presented in abstract form (Bohotin et al. 2005; Duncan et al. 2005).

METHODS

Subjects

Nine normal volunteers (four females, five males; one left-handed) were recruited for a vibrotactile fMRI study. The Research Ethics Board of the Montreal Neurological Institute and Hospital approved the study. All subjects gave written informed consent and were financially compensated for their time commitment to this study.

Stimuli

Vibrotactile stimuli (75 Hz, duration = 3, 3.25, 3.5, or 4 s) were software-generated (CoolEdit) using wav files and were played through two amplifiers (one per stimulator) that were connected to the sound card of a portable computer. The stimuli were delivered through a small piece of balsa wood (8 x 16 mm) fixed to each of the two custom-built piezoelectric stimulators. The stimulators were placed on the right volar surface of the forearm at the level of the C6 dermatome. The distal stimulator was positioned transversally on the first anterior third of the arm (a few centimeters from the distal wrist crease) and the proximal stimulator was placed within 1 cm of the distal one.

Experimental paradigm

The experiment consisted of three trial types: detection, localization, and passive stimulation tasks (see Fig. 1 for the stimulation protocol). The design randomized the conditions within each experimental run as individual blocks of trials that shared a common behavioral instruction: detection, localization, or passive (no motor responses necessary). Prior to the scanning session, all subjects performed a few “practice” trials to become familiarized with the stimuli and the experimental design. Each trial began with a 4-s cue period, during which subjects viewed a written command on a computer monitor indicating task instructions for the current trial: “detection trial,” “localization trial,” or “passive trial”. After the “cue,” a vibrotactile stimulus (3–4 s in duration) was then delivered to one of the two locations on the right forearm. For the detection task only, subjects had to attend to the vibrotactile stimulus for its full duration to indicate its “offset” (end) by pressing a mouse button with their left hand. Following the stimulation period, a delay of 4 s (delay 1) was interposed before the response period (response, 4 s). At the response period in localization trials, subjects viewed on the computer monitor one of the two possible localization questions (either “distal?” or “proximal?”), to which they indicated their response (“yes” or “no”) by pressing one of two keys on the mouse. Presentation of the localization question, which pertained to the relative position of the stimulus, was randomized across trials to ensure that subjects did not prepare their motor response in advance, thus minimizing activation of motor planning areas. This ensured that stimulus and delay periods in all tasks would be comparable in terms of a minimized influence of motor activity. In the passive and offset tasks, subjects received no instructions during the response period (which could thus be considered as “delay 2”) and were required to make no movements. Thus in the passive task, subjects received the vibrotactile stimulus, but were not required to detect its offset or discriminate its location.

fMRI acquisition

All psychophysical experiments were conducted within the fMRI research suite at the McConnell Brain Imaging Center (BIC) of the Montreal Neurological Institute at McGill University. Functional and

![Stimulation Protocol](image_url)

FIG. 1. The experiment consisted of 3 trial types: passive, detection, and localization, in which subjects always received a single stimulus from one of the 2 stimulators placed on their arm. During the passive task, subjects received the stimulus, but no response was required at the end of the stimulus or at the end of the trial. During the detection task, subjects detected the offset (end) of the stimulus and signaled their response by pressing a mouse key with their left hand. No response was required at the end of the trial. During the localization task, subjects received the stimulus and, after a 4-s delay, they were asked to indicate by pressing a mouse key with their left hand whether the stimulus was distally or proximally located. Subjects were not required to detect the offset of the stimulus.
anatomical images were obtained on a 1.5-T Siemens Sonata scanner (Siemens, Erlangen, Germany) using a standard head coil. The MR technician fixed the head of each subject in a comfortable position and immobilized it with a vacuum bag. Subjects were instructed to refrain as much as possible from moving throughout the imaging session and were given earplugs to reduce the noise from the scanner. Subjects viewed written task instructions on a computer monitor (projected on a screen visible in a mirror fixed on the head coil) and made their responses with the hand contralateral to the stimulation (during the detection and localization tasks) using an MR-compatible mouse. Each session consisted of an anatomical scan and four to six functional scanning runs. The anatomical scans were T1-weighted high-resolution scans (repetition time [TR] = 22 ms, time to echo [TE] = 20 ms, flip angle = 30°, field of view [FOV] = 256 mm, 1-mm isotropic sampling).

The functional scans were collected using a blood oxygen level–dependent (BOLD) protocol with a T2*-weighted gradient echo-planar imaging (EPI) sequence (TR = 3.0 s, TE = 51 ms, flip angle = 90°, 64 × 64 matrix, 163 volume acquisitions). The scanning planes were oriented parallel to the anterior commissure–posterior commissure line and covered part of the brain from the top of the cortex to the base of the cerebellum (35 contiguous 4-mm-thick axial slices, voxel size = 4 × 4 × 4 mm). Each functional scanning run consisted of four detection, four localization, and four passive trials.

Data analysis

Functional data and anatomical images were analyzed using Brain Voyager QX (Brain Innovation, Maastricht, The Netherlands). Functional images were preprocessed (interscan slice time correction, three-dimensional [3D] motion correction, high-pass filtering), interpolated to 1 × 1 × 1 mm³, and coregistered to a 3D anatomical image. Within a trial, each distinct period that contained a stimulus, delay, or response event was modeled as a regressor; likewise, the instruction cue period and baseline were defined as regressors. Each event was further subcategorized according to trial type (passive, offset detection, localization). All of the regressors were convolved with a canonical hemodynamic response function (Boynton et al. 1996). For each subject, a general linear model (GLM) was computed and the overall model fit was assessed using an F statistic. Group activations (random-effects analysis) were thresholded at P < 0.05 (t = 4.67, corrected for multiple comparisons). Coordinates of loci of activation are given in Talairach space (Talairach and Tournoux 1988).

Additional ANOVA analyses on the % BOLD signal associated with stimulus presentation were made to document the differential effect of the three tasks on specific sensory regions of interest—i.e., cortical regions commonly associated with the processing of tactile stimuli. First, the GLM analysis was performed to generate the cluster of areas activated by the stimulus (compared with the resting baseline). Then the % BOLD signal was extracted from each brain region of interest (left SI, left and right SII, left and right IC) and for each individual subject. We averaged the signal within 5–13 s after the onset of the vibrotactile stimulus (to obtain a standardized 8-s BOLD response that included the peak of the hemodynamic response curve). This analysis was done separately for each trial type (passive, offset detection, and localization).

We performed a repeated-measures ANOVA to test for a main effect of the task—i.e., to test the null-hypothesis that task conditions (offset-detection, localization, and passive stimulation) have no modulatory effect on stimulus-evoked brain activation. To account for subject-related variance we included a dummy variable coding for each participant. This procedure creates one categorical covariate for each subject, the variance of which is removed before estimating the effects associated with the variables of interest.

RESULTS

Psychophysical data

During the detection task, subjects correctly identified the offset of the vibrotactile stimulation on 95.6% (SD: 2.13) of the trials. The mean reaction time (RT) to detect the stimulus offset was 434.45 ms (SD: 147.72 ms). The speed of the subjects’ responses (1/RT) signaling detection of the offset did not differ significantly for the varying stimulus durations; however, a modest trend toward faster responses for longer stimulus durations (3-s stimulus: 2.47 s⁻¹; 3.25-s stimulus: 2.52 s⁻¹; 3.5-s stimulus: 2.58 s⁻¹; 4-s stimulus: 2.73 s⁻¹) indicates that subjects attended to and anticipated the offset of the stimuli. (The monotonic relationship between response speed and stimulus duration is consistent with task-related behavior in a detection task with discernable differences in the probability of the target cue.)

During the localization task, subjects correctly identified the relative position of the stimulus on the right forearm (proximal or distal) on 95.74% (SD: 5.32) of the trials, with a mean RT of 705.73 ms (SD: 128.4 ms) for successful trials and a mean of 1,687.57 ms (SD: 1,459.05 ms) for failed trials, measured from the presentation of the localization question on the monitor at the start of the response period. The similar success rates for the detection and localization tasks suggest that the two active conditions were well balanced for difficulty and did not differ substantially in the vigilance and attention directed toward the stimuli.

During the passive task, subjects refrained from any motor responses on 100% of the trials. In total, these behavioral data indicate that the subjects understood the individual tasks and responded appropriately in accordance to the cue, which signaled task instruction at the beginning of each trial.

fMRI data

For each trial type (detection, localization, passive) regressors for the cue, stimulus, the poststimulus delay period, response, and baseline were included in the design matrix. Although no motor responses were required for the passive and detection tasks, the corresponding time period predictors were nevertheless included as regressors to ensure that subjects were performing the task correctly and to balance the design matrix. Especially in the instance of the poststimulus delay period it was of keen interest to examine the maintenance of the location of the stimulus during the localization trials. All the regressors (cue, stimulus, poststimulus delay period, response, baseline) for each trial type (detection, localization, passive) were convolved with a canonical hemodynamic response function (Boynton et al. 1996).

Stimulus-evoked activation (random-effects analysis)

Within areas of the cortex commonly associated with the processing of tactile stimuli (sensory regions of interest), both detection and localization tasks produced reliable activation related to the vibrotactile stimulation that was applied to the volar surface of the right forearm compared with the resting baseline, in contralateral SI/PPC, bilateral SII, and bilateral aIC (t > 3.34; P < 0.01) (Fig. 2). During the passive task the vibrotactile stimulus-evoked activation was associated with
TABLE 1. Areas of stimulus-evoked activation for passive, detection, and localization tasks

<table>
<thead>
<tr>
<th>Brain Area</th>
<th>Passive</th>
<th>Detection</th>
<th>Localization</th>
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<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>Left</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L SI/PPC</td>
<td>−57</td>
<td>−31</td>
<td>35</td>
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<tr>
<td>L SII</td>
<td>−54</td>
<td>−25</td>
<td>22</td>
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<tr>
<td>L aIC</td>
<td>−27</td>
<td>17</td>
<td>9</td>
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<tr>
<td>L SMA</td>
<td>—</td>
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<td>—</td>
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<tr>
<td>L inferior frontal</td>
<td>−57</td>
<td>2</td>
<td>10</td>
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<td>L PPC</td>
<td>—</td>
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<td>L thalamus</td>
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<td>L cerebellum</td>
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<td>Right</td>
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<tr>
<td>R SI</td>
<td>51</td>
<td>−34</td>
<td>45</td>
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<tr>
<td>R SII</td>
<td>57</td>
<td>19</td>
<td>25</td>
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<tr>
<td>R aIC</td>
<td>36</td>
<td>11</td>
<td>−7</td>
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<tr>
<td>R inferior frontal/mid IC</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>R PPC</td>
<td>45</td>
<td>35</td>
<td>13</td>
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<tr>
<td>R inferior frontal</td>
<td>51</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>R premotor</td>
<td>21</td>
<td>−10</td>
<td>61</td>
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<tr>
<td>R SMA</td>
<td>—</td>
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<tr>
<td>R thalamus</td>
<td>21</td>
<td>−58</td>
<td>64</td>
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<tr>
<td>R putamen</td>
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<td>13</td>
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<tr>
<td>R cerebellum</td>
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Areas of vibrotactile stimulus-evoked activation for the passive (P), detection (D), and localization (L) tasks. Coordinates are given in Talairach space (Talairach and Tournoux 1988). Medial–lateral (X), anterior–posterior (Y), and superior–inferior (Z) stereotaxic coordinates (in millimeters) are relative to midline, anterior commissure, and commissural line, respectively (positive values are right, anterior, and superior). L, left; R, right; SMA, supplementary motor area; SI, primary somatosensory cortex; SII, secondary somatosensory cortex; IC, insular cortex; aIC, amodal insular cortex; PFC, prefrontal cortex; PPC, posterior parietal cortex. t-values that have a corresponding value of P \leq 0.05 (the threshold for significance corrected for multiple comparisons corresponds to a t-value of 4.67) are in bold. Results are from performing a random-effects analysis.

FIG. 2. Vibrotactile-related activation for the (A) detection, (B) localization, and (C) passive tasks. A: during the detection task, stimulus-evoked activity was found in contralateral (L) primary somatosensory cortex/posterior parietal cortex (SI/PPC), bilateral secondary somatosensory cortex (SII), and anterior insular cortex (aIC) (random-effects analysis). B: during the localization task, stimulus-evoked activity was found in bilateral SII and aIC, and in SI/PPC, although to a lesser extent than that for the detection task. C: during the passive task, stimulus-evoked activity was found in bilateral SII. No significant activation was seen in SI/PPC or in aIC.

significant activation in bilateral SII (Fig. 2). Additional areas of activation, outside of the sensory regions of interest, are detailed in Table 1 for the three tasks.

To investigate the relationship of the different active tasks (detection, localization) relative to the passive task, the stimulus-evoked signal change attributed to the three different tasks, with a dummy variable as a covariate to account for subject-related variance. Results of this analysis revealed a significant interaction (F = 2.612; P = 0.015) between the task factor (passive, detection, and localization) and the brain area factor (left SI/PPC, left SII, right SII, left IC, and right IC), as well as a main effect of task (F = 3.518; P = 0.036) and a main effect of brain area (F = 3.618; P = 0.015). To interpret the main effects and the different levels of those effects, we performed an analysis of contrasts that did not include the subjects as a covariate (to retain sufficient residual degrees of freedom). The localization task was associated with a significantly greater increase in stimulus-related activation in contralateral (left) SI/PPC (F = 5.794; P = 0.043) compared with that observed during the passive task. Additionally, both the detection and localization tasks were associated with significantly greater BOLD responses in left and right IC, compared with that observed in the passive task (F > 10.0; P < 0.001).

Activity during the poststimulus delay (random-effects analysis)

We observed significant BOLD signal in right aIC that was maintained after the termination of the stimulus during delay 1 (vs. resting baseline) in the localization trials only. The activation levels in right aIC for the other two trial types were not significantly different from resting baseline (Fig. 3). In addition, we observed significant BOLD signal observed within the different brain areas of interest (left SI/PPC, left SII, right SII, left IC, and right IC) was compared among the different trial types. We performed a repeated-measures ANOVA on the % BOLD signal change attributed to the three different tasks, with a dummy variable as a covariate to account for subject-related variance. Results of this analysis revealed a significant interaction (F = 2.612; P = 0.015) between the task factor (passive, detection, and localization) and the brain area factor (left SI/PPC, left SII, right SII, left IC, and right IC), as well as a main effect of task (F = 3.518; P = 0.036) and a main effect of brain area (F = 3.618; P = 0.015). To interpret the main effects and the different levels of those effects, we performed an analysis of contrasts that did not include the subjects as a covariate (to retain sufficient residual degrees of freedom). The localization task was associated with a significantly greater increase in stimulus-related activation in contralateral (left) SI/PPC (F = 5.794; P = 0.043) compared with that observed during the passive task. Additionally, both the detection and localization tasks were associated with significantly greater BOLD responses in left and right IC, compared with that observed in the passive task (F > 10.0; P < 0.001).
tion, during the delay in localization trials activation was also seen in the right hemisphere of the premotor area (X = 30, Y = −25, Z = 58, t = 6.14, P < 0.001), the posterior parietal cortex (X = 24, Y = −46, Z = 46, t = 9.11, P < 0.001), and the putamen (X = 21, Y = −1, Z = 4, t = 5.97, P < 0.001) and also in the left hemisphere the supplementary motor area (X = −3, Y = −4, Z = 55, t = 6.51, P < 0.001), the inferior parietal lobule (X = −54, Y = −58, Z = 34, t = 8.6, P < 0.001), the inferior frontal gyrus (X = −57, Y = 8, Z = 22, t = 10.22, P < 0.001), mid insula (X = −45, Y = 8, Z = 5, t = 6.8, P < 0.001), and the anterior cingulate cortex (X = −12, Y = 2, Z = 37, t = 6.24, P < 0.001).

**Discussion**

This study examined the cerebral responses to vibrotactile stimulation relative to different psychophysical and cognitive demands, which included passive stimulation, detection of stimulus offset, and stimulus localization tasks. Results show that the level of cerebral activation depended on the task demands, which differentially modulated specific brain areas involved in the processing of innocuous vibration stimuli.

**Task-related modulation of stimulus-evoked activity within specific brain regions**

**Secondary somatosensory cortex.** Within SII, significant levels of stimulus-evoked activity were observed during all three tasks (passive, detection, and localization). The bilateral nature of this activation is generally consistent with the existing literature. Electrophysiological studies have shown that SII contains cells that have bilateral receptive fields (Burton et al. 1998; Carreras and Andersson 1963; Petit et al. 1990; Whitsel et al. 1969) and therefore respond to mechanical cutaneous stimuli applied to both sides of the body (Favorov et al. 2006; Tommerdahl et al. 2005b). Likewise, functional brain imaging studies have also reported vibrotactile stimulus-evoked activation levels in bilateral SII (Burton et al. 2004; Golaszewski et al. 2006; Li et al. 2007; Nelson et al. 2004a, b).

In the present study significant vibrotactile-related activation was observed in SII during both passive and active tasks; however, responses during the detection task were somewhat stronger, but not significantly so compared with the other tasks. Results of previous studies are rather inconsistent regarding the modulation of tactile-related activity in SII by specific task demands. Several authors have noted increased activity in this region in response to more challenging tasks (Burton et al. 1999; Johansen-Berg et al. 2000; Nelson et al. 2004a). For example, a recent fMRI study found that the extent of activation in SII in response to a nonattention-demanding task was diminished compared with a variety of complex cognitive vibrotactile stimulation tasks (Burton et al. 2008b); however, an electrophysiological study in nonhuman primates demonstrated decreased neuronal firing during an attention task (Burton et al. 1997). Further conflicting results come from a recent somatosensory steady-state evoked-potential study demonstrating that attention toward stimuli applied to the hand, compared with an unattended condition, had no modulatory effect on activation within SII (Giabboni et al. 2007). The various results from these previous studies may reflect differences in task design. Results from our present study indicate that activation evoked by a vibrotactile stimulus may be observed in SII, even in a passive task that requires minimal attention to the stimulus site. The identical activation patterns seen in SII during both active and passive tasks indicate that this region is not heavily influenced by cognitive modulation.

**Primary somatosensory and posterior parietal cortex.** Within the contralateral parietal cortex (SI/PPC), the active tasks were associated with reliable levels of vibrotactile-related activity. When compared with the resting baseline, activation during the detection task was strongly significant. Activation observed during the localization task showed a trend toward significance, when compared with the resting baseline, and was greater than that observed during the passive task. Differences in SI/PPC activation between active and passive tasks were more evident using an ANOVA performed on the stimulus-related activity extracted from the individual subject analyses, an approach that avoids the problem of signal dilution arising from a strict spatial averaging of data around the central sulcus, a region of pronounced interindividual anatomical variability (Vincent et al. 2006).

Our observations of stronger stimulus-related activation in the area of SI/PPC during active tasks are consistent with results from a number of previous studies that have demonstrated increased SI activity during more active tasks, such as frequency discrimination (Li et al. 2007; Soros et al. 2007) or during conditions of increased attention directed toward vibrotactile stimuli (Meyer et al. 1991; Staines et al. 2002). The potential importance of this region for the performance of our active tasks is underscored in a recent study (Porro et al. 2007), which demonstrated disrupted spatial localization of tactile stimuli after brief transcranial magnetic stimulation (TMS) pulses were applied to the PPC; even greater effects on psychophysical performance had been reported in a previous study where TMS applied to the sensorimotor cortex profoundly interrupted detection of tactile stimuli (Andre-Obadia et al. 1999; Seyal et al. 1997). Thus both detection and localization tasks may be expected to modulate tactile-related activation in the region of SI/PPC.

Most previous studies have indicated that the response to innocuous cutaneous stimuli in contralateral SI is usually greater than that observed in ipsilateral SI for electrophysiological responses recorded in primates (Tommerdahl et al. 2005a) and for the BOLD signal measured with fMRI in humans (Blatow et al. 2007; Burton et al. 2004; Golaszewski et al. 2006). However, during all three tasks in the present study (including the passive presentation of stimuli), vibrotactile...
stimulation evoked reliable activation in the ipsilateral (right) parietal cortex. Our findings are consistent with a few studies that report asymmetrical neural correlates of passive tactile processing lateralized to the right hemisphere, regardless of which hand is stimulated (Bodegard et al. 2001; Harada et al. 2004; Kitada et al. 2006). A right hemispheric lateralization of activation in parietal cortex has also been demonstrated in the processing of passively delivered innocuous and noxious thermal stimuli, irrespective of which arm received the stimulation (Coghill et al. 2001). Passive (Van de et al. 2005; Zhang et al. 2005) and active (Preuschhof et al. 2006; Ricciardi et al. 2006) tactile discrimination has also been found to elicit bilateral activation of parietal regions.

In the present study, we cannot rule out a possible contribution toward activation in the right parietal cortex by the subjects’ left-hand responses that signaled detection of the offset of vibrotactile stimuli in the detection task or to the left-hand response indicating the location of the stimulus at the end of the localization trials. However, motor responses in the localization task were delayed 4 s following the termination of the stimuli, and subjects could not plan the specific motor response until reading the instruction cue at the beginning of the response period. Likewise, in the passive task, no movement of the left hand was necessary. Therefore right activation in SI/PPC, associated with delivery of the vibrotactile stimuli, is unlikely to be related to movement of the left hand in the passive and localization tasks.

ANTERIOR INSULAR CORTEX. In both the left and right aIC, presentation of the vibrotactile stimuli during the active tasks (detection and localization stimulus periods vs. baseline) was associated with significant activation, which was significantly stronger than that observed during the passive task (active tasks stimulation period vs. passive task stimulation period). As was noted in the discussion of contralateral SI, these findings in bilateral aIC are consistent with neuroimaging studies of vibro-tactile processing demonstrating aIC activation during more attention-demanding tasks such as frequency discrimination (Li et al. 2007; Soros et al. 2007). Considering the potential role of attention in increasing vigilance, these active tasks in the present study may have been associated with changes in arterial pressure, heart rate, or respiration, and thus the task-related activity that we observe in aIC is entirely consistent with a major role of this region in viscero-sensory (Oppenheimer et al. 1992) and interoceptive processing (for review see Craig 2009).

Future studies could test this hypothesis regarding the influence of attention on viscero-sensory processing in the aIC by recording physiological measures during a scanning experiment involving active and passive tasks. For example, a recent fMRI study conducted in our laboratory correlated electrodermal responses with cerebral activity during the random presentation of noxious and innocuous stimuli (Dubé et al. 2009). Activation within the aIC was evoked by the noxious stimuli (pain minus warm conditions), as expected. In addition, activation in aIC was correlated with electrodermal activity evoked during both innocuous and noxious stimulation. This finding possibly reflects the stress experienced by subjects during the expectation of painful stimuli, which were presented randomly during the experiment.

Although the aIC has been implicated in mediating the perception of noxious stimuli (Akparian et al. 2005) and the regulation of autonomic responses (as noted earlier), increasing evidence underscores the importance of this region in the perception of innocuous sensory stimuli, including vibration (Burton et al. 1993; Soros et al. 2007), touch (Olausson et al. 2002), and nonpainful mechanical stimuli (Lui et al. 2008). Our observation of vibration-related activity in aIC is consistent with the findings from these previous studies and supports the notion that the insula is a region of integration for multisensory input.

The IC connects somatosensory cortices with the prefrontal cortex (Burton and Sinclair 2000a; Constantinidis and Procyk 2004), a region implicated in working memory (for a review see Linden 2007). Based on this anatomical connectivity, the IC is at the crossroads for integrating both the cognitive (attention and saliency) and sensory (frequency and location of stimulation) aspects of perception of cutaneous vibrotactile stimuli. Consistent with these data demonstrating a multisensory integration within this region, the right aIC has been implicated as part of a network of cortical areas involved in attention to innocuous sensory events (Downar et al. 2000, 2002). In line with these findings is a recent fMRI study that showed that after lapses in attention during the performance of a repetitive task, a network of brain regions including the aIC was reactivated, suggesting that this region plays a role in restored attentional processes (Weissman et al. 2006). Thus the functional implications from these previous studies of the insular cortex are fully consistent with the preferential activation of this area that we observed during the detection and localization tasks and the relative absence of insular activation we observed when subjects were neither attending to nor localizing stimuli during the passive task.

In sum, the most parsimonious interpretation of the stimulus-evoked activation we observed in the aIC during the active tasks is consistent with this region’s proposed roles in attention and in viscero-sensory processing (the latter of which is perhaps an obligatory consequence of the former). Recent hypotheses regarding the function of aIC have emphasized its potential role in interoceptive processing, including an appreciation of painful or tissue-threatening stimulation. Results from our study indicate that interoceptive stimuli (such as innocuous vibrotactile stimulation of the skin) may also be associated with activation in aIC, possibly through modulation of autonomic responses by directed attention within the context of a psychophysical discrimination paradigm. In addition, some electrophysiological and fMRI studies have previously demonstrated a crude somatotopic organization in this region indicating that the aIC could aid in localizing stimuli applied to the body (Henderson et al. 2007; Ostrowsky et al. 2002; Penfield and Faulk Jr 1955). Future studies examining the role of the aIC in interoceptive and exteroceptive processing could contrast two tasks of equal difficulty that engaged these separate processes (such as monitoring one’s breathing compared with discriminating stimuli).

ACTIVITY DURING THE POSTSTIMULUS DELAY. During the localization task, significant activation was observed in the right aIC during both the poststimulus delay (delay 1) and at the response portion of the trial. A previous study, using a vibrotactile working-memory paradigm, also reported sustained activ-
ity in bilateral aIC following termination of the stimulus (Soros et al. 2007). Furthermore, other neuroimaging studies have implicated these regions in the temporal processing of stimuli (Rieckert et al. 2000; Wise et al. 1999; Wong et al. 2004). Taken together, these results suggest that the aIC region may be involved in maintaining spatial aspects of sensory stimuli in short-term memory.

An alternative interpretation of the activity we observed in the aIC during the delay period assumes an increase in stress during the anticipation of the motor response that was required during the localization task, but not during the detection or passive tasks. This interpretation is consistent with the region’s previously described role of viscerosensory processing. The paradigm design of the present study cannot rule out the potential implications of stress and response anticipation during the delay period, which may have been present in the localization trials, but not in the detection trials. However, we recently conducted a similar study that used an active discrimination/memory task as well as an active control task. During the interstimulus delay period, both tasks were characterized by anticipation of a second stimulus, continued attention toward the stimuli, and planning for identical motor responses to signal the detection of the stimulus offset; however, only the discrimination task required the subjects to remember the previous stimulus to make a subsequent discrimination. Although arousal, attention, and motor planning were similar in the two tasks, activity in both left and right aIC was greater during the discrimination task, which required a short-term memory of the previous stimulus, compared with that of the control task, which had no inherent memory requirements (Albanese et al. 2005). Thus although the present study cannot rule out the possible influence of attention and motor planning on aIC activity during the delay period preceding the discrimination response, our previous data suggest that some of this activity may be related to memory of the previous stimulus, which was required to make the subsequent response during the localization trials.

Activation during the delay period was also seen during the localization task in the posterior parietal and motor cortices contralateral to the subjects’ press of the response button. This activation may reflect motor preparation that precedes the response and is consistent with previous interpretations of activation in this region reported in a number of electrophysiological and fMRI studies (Hanakawa et al. 2008; Libet 1985; Medendorp et al. 2008). Our experimental protocol was designed to minimize motor planning by delaying the specific question (and appropriate movement) until the end of the trial; however, during this delay period subjects may have been preparing several alternative responses with fingers on the contralateral hand—a strategy that could be associated with activation observed in the posterior parietal and motor cortices.

Comparison of detection and localization tasks

Although we observed a profound enhancement of stimulus-related cortical responses during performance of the two active tasks, compared with the passive task, we were somewhat surprised by the relative similarity of responses associated with the two different active tasks. Contrary to our expectations, stimulus-related activation during the localization task was not substantially greater than that of the other tasks in regions where one might have expected a functional specificity for the spatial processing of tactile information. In fact, localization-related activation during the presentation of the vibrotactile stimuli was generally less than that observed during the corresponding period of the detection task throughout the different areas of the brain that process tactile stimuli (see Table 1). Lower activation levels observed in the localization task could be due to the shorter time needed by the subjects to make the spatial discrimination, compared with the detection task, which required the subjects to attend to the entire duration of the stimulus to detect its offset. Psychophysical data recorded in our laboratory during a similar spatial discrimination task indicated that subjects required <1.5 s to localize a vibrotactile stimulus (Bohbotin et al. 2005), suggesting that subjects in the present imaging study might not have needed to attend to the entire duration of the stimulation period to correctly identify the relevant spatial characteristics of the stimuli.

Conclusions

We have shown that vibrotactile-related fMRI activation within SI/PPC and aIC is enhanced during the performance of active psychophysical tasks, compared with the relative lack of activity observed in these regions during passive presentation of the identical stimuli. Active participation in the detection and localization tasks required increased levels of attention and cognitive processing to correctly identify spatial and temporal aspects of the stimulus. The increased activation observed during the active tasks within contralateral SI/PPC and bilateral aIC argues for the preferential participation of these areas in functions related to the detection and localization of vibrotactile stimuli, compared with the secondary somatosensory cortices, where stimulus-related activity was less affected by apparent differences in attention and cognitive demand. The stimulus-related activation in aIC highlights a role for this area in the processing of innocuous vibrotactile stimuli. Furthermore, the activation associated with the poststimulus delay, during which participants maintained information concerning the location of the stimulus, implicates this area in short-term retention of innocuous somatosensory information.

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References

Albanese M-C, Duerden EG, Peters TM, Rainville P, Duncan GH. Latera-
ralization of responses in human cortex associated with tactile memory.
Andre-Obadia N, Garcia-Larrea L, Garassus P, Mauguie`re F. Timing and
characteristics of perceptual attenuation by transcranial stimulation: a study
using magnetic cortical stimulation and somatosensory-evoked potentials.
Akparian AV, Bushnell MC, Treede RD, Zubieta JK. Human brain mech-
anisms of pain perception and regulation in health and disease. Eur J Pain
Blakemore SJ, Bristow D, Bird G, Frith C, Ward J. Somatosensory
activations during the observation of touch and a case of vision-touch


