Evidence for Interhemispheric Processing of Inputs From the Hands in Human S2 and PV

ELIZABETH DISBROW,1,3 TIM ROBERTS,3 DAVID POEPPEL,4 AND LEAH KRUBITZER2
1Department of Neurology and 2Department of Psychology, Center for Neuroscience, University of California, Davis 95616; 3Biomagnetic Imaging Laboratory, Department of Radiology, University of California, San Francisco, California 94143-0628; and 4Department of Linguistics and Department of Biology, University of Maryland at College Park, College Park, Maryland 20742

Received 17 August 2000; accepted in final form 22 January 2001

Disbrow, Elizabeth, Tim Roberts, David Poeppel, and Leah Krubitzer. Evidence for interhemispheric processing of inputs from the hands in human S2 and PV. J Neurophysiol 85: 2236–2244, 2001. In the present investigation, we identified cortical areas involved in the integration of bimanual inputs in human somatosensory cortex. Using functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG), we compared the responses to unilateral versus bilateral stimulation in anterior parietal cortex and areas in the Sylvian fissure of the contralateral hemisphere. The extent of fMRI activation on the upper bank of the Sylvian fissure, in the second somatosensory (S2) and the parietal ventral (PV) areas, was significantly larger for bilateral stimulation than for unilateral stimulation. Using MEG, we were able to describe the latency of response in S1 and S2/PV to unilateral and bilateral stimulation. The MEG response had three components under both stimulus conditions. An early peak in S1 at 40 ms, a middle peak in S2/PV at 80–160 ms, and three late peaks in S2/PV at 250–420 ms. There was an increase in magnetic field strength in S2/PV to bilateral stimulation at 300–400 ms post stimulus. The fMRI results indicate that, as in monkeys, S2/PV receives inputs from both the contralateral and ipsilateral hand. The MEG data suggest that information is processed serially from S1 to S2. The very late response in S2/PV indicates that extensive intrahemispheric processing occurs before information is transferred to the opposite hemisphere. The neural substrate for the increased activation and field strength at long latencies during bilateral stimulation can be accounted for in three ways. Under bilateral stimulus conditions, more neurons may be active, neuronal firing rate may increase, and/or neural activity may be more synchronous.

INTRODUCTION

A unique behavior exhibited by humans is their ability to manipulate the physical environment with their hands. Yet relatively little is known in humans about the areas of the neocortex involved in complex behaviors such as tactile discrimination and recognition, manual dexterity, and bilateral coordination of the hands. To understand complex behavior such as bilateral coordination of the hands, it is important to examine where such information is processed and how these regions are organized and interconnected. One of the requisites for these behaviors is the integration of inputs across the hand and between hands. We define integration as the combination of the inputs from different neurons with discrete receptive fields across the surface of the skin. For example, cortical regions involved in the discrimination of object size and shape must access inputs from different locations of one hand, such as various portions of several digits. For tasks involving both hands, inputs from both topographically matched and mismatched locations of both hands must ultimately be combined.

In nonhuman primates, our understanding of cortical areas involved in integrating inputs across or between the hands has increased substantially. Neurons in areas in posterior parietal cortex and the lateral sulcus have large receptive fields that encompass much larger skin surface areas of the hand than receptive fields for neurons in areas 3b or 1 (i.e., compare Nelson et al. 1980 with Krubitzer et al. 1995; Whitsel et al. 1969). While the existence of neurons with bilateral receptive fields on the hands has been shown in several somatosensory cortical areas including areas 2 and 5 (Iwamura 1999; Iwamura et al. 1994), area 7b (Dong et al. 1994; Robinson and Burton 1980a), and the second somatosensory area (S2) (Robinson and Burton 1980a,b; Whitsel et al. 1969), they are most common in S2, where their incidence is reported to be as high as 90% (Whitsel et al. 1969). Cortical fields in the lateral sulcus and insula other than S2 have been described in nonhuman primates (Cusick et al. 1989; Krubitzer et al. 1995; Robinson and Burton 1980a,b), but the number, extent, and internal organization of these fields have not been completely characterized.

Similarly in humans, the number, extent and internal organization of fields on the upper bank of the lateral sulcus, or Sylvian fissure, have not been completely described. As in other primates (Burton et al. 1995; Krubitzer and Kaas 1990; Krubitzer et al. 1995), humans have an S2 and a parietal ventral area (PV; probably analogous to S1F and S1Fr, respectively, of Whitsel et al. 1969), which each contain a topographically organized representation of cutaneous receptors (Disbrow et al. 2000). These two areas are mirror symmetric representations of the body’s surface that are joined at the representations of the hands, feet, and face, and flanked by more proximal body part representations (Fig. 1). As in nonhuman primates, there appears to be a number of additional cortical fields along the upper bank of the Sylvian fissure that are differentially active.
used the 3-in surface coil because of the superior signal-to-noise ratio.

a whole head coil, and a 3-in surface coil (GE Medical Systems, participating in the study. Imaging was performed using a standard all right handed, aged 25–50 yr) provided informed consent before participating. In all subjects, data were acquired from both hemispheres offered by the whole head coil.

First, an anatomical high-resolution three-dimensional SPGR (3-dimensional steady precession gradient-recalled) series (acquisition: axial, interleaved, 256 × 256 matrix, FOV 40 × 40; 124 slices, 1-mm slice thickness, repetition time = 35 ms, echo time = 6 ms, flip angle = 30°, 1 NEX, fatsat) was collected for the determination of Talairach coordinates. Then an ultrafast echo planar gradient echo imaging sequence designed to detect variations in local T2* (repetition time = 2 s, echo time = 60 ms, flip angle = 60°) was used. For both coils a 256 × 128 matrix was used with a field of view of 40 × 20 cm, a slice thickness of 5 mm (0.5-mm gap) and thus a voxel (3-dimensional pixel) size of 1.56 × 1.56 × 5 mm.

FIG. 1. The second somatosensory area (S2) and parietal ventral area (PV) homunculi displayed on an axial drawing of the left hemisphere. The figure of the whole brain indicates the location of the axial drawing with respect to the Sylvian fissure (SF). Rostral is to the left and lateral is to the bottom of the axial drawing.

under a number of different stimulus conditions. Burton et al. (1993) suggested two areas of activation along the parietal operculum and insula. Further, they have described two foci of activation on the parietal operculum in response to cutaneous versus deep stimulation (Burton et al. 1997). Ledberg et al. (1995) described differential activation in cortex of the Sylvian fissure in response to microgeometric versus macrogeometric tactile stimuli. Recently we described two fields, in addition to S2 and PV, on the upper bank of the Sylvian fissure, one rostral to PV that we termed the rostral lateral area (RL), and one caudal to S2 that is in the location of area 7b in nonhuman primates (Disbrow et al. 2000). However, whether these areas are involved in integrating inputs from the hands is not known.

The present series of studies combine functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) techniques to address two questions. First, where in the human Sylvian fissure are bimanual inputs processed? More specifically, are the somatosensory areas described in the preceding text activated differentially by stimulation of one hand versus both hands? The use of fMRI is ideal for addressing this question because it provides high spatial resolution. Second, when are bimanual inputs processed in the human Sylvian fissure? That is, what is the temporal pattern of activation of cortical somatosensory areas? Although cortical connections cannot be directly studied in humans, MEG has high temporal resolution allowing us to make inferences about connectivity within and between hemispheres.

METHODS

fMRI

All studies were performed with the approval of the institutional human studies committee. Twelve healthy subjects (5 men, 7 women, all right handed, aged 25–50 yr) provided informed consent before participating in the study. Imaging was performed using a standard clinical GE 1.5 Tesla scanner. Two radio frequency coils were used, a whole head coil, and a 3-in surface coil (GE Medical Systems, Milwaukee, WI). A single coil was used for each subject. We initially used the 3-in surface coil because of the superior signal-to-noise ratio.

However, the difference in activation patterns appeared to be negligible and not worth losing the ability to collect data from both hemispheres offered by the whole head coil. Cross-correlation analysis was used to determine significantly active voxels. A correlation threshold of r = 0.3 (alpha level of P < 0.02) was used with an in-plane cluster threshold of four voxels. Patterns of activation were superimposed on high resolution three-dimensional images. The centroid of the S2/PV activation was calculated, and the standardized stereotaxic coordinates of the centroids were determined (Talairach and Tournoux 1993). These coordinates were then compared within subjects, using a paired-t-test, to determine if there was a significant difference for the location of activation of S2/PV for the uni- versus bilateral stimulus conditions.

MEG

Twelve subjects (8 men, 4 women, all right handed, aged 25–50 yr; not the same subjects used for the fMRI study) provided informed consent before participating. In all subjects, data were acquired from the left hemisphere during stimulation of the right index finger as well as the right and left index fingers. Pneumatically driven mechanical stimuli were repeated 200–250 times. Neuromagnetic fields were recorded in a shielded room using a 37-channel biomagnetometer system (Magnes, BTi, San Diego, CA). The 37 first-order gradiometers are arranged in a concentric radial
distribution over a concave surface with an intercoil separation of 2.2 cm and an angular field of view of $\sim 70^\circ$. The diameter of the sensor array head is 14 cm. Epochs of 500-ms duration (plus 100-ms pre-stimulus) were acquired with a 1.0-Hz high-pass cutoff and a sampling rate of 1 kHz. The sensor array was positioned over somatosensory cortex. The sensor was initially optimized for recording early S1 responses (central-parietal) and subsequently moved to a more lateral and anterior position to better record from the S2/PV area of the lateral sulcus (central-temporal).

Epoch data that were time locked to stimulus onset were averaged and band-pass filtered (8–40 Hz) before additional analysis. Parameters that were evaluated as a function of uni- or bimanual stimulation include the amplitude of the evoked response, and root mean square activity across channels (RMS). The position, orientation, and strength of the estimated dipoles was computed using a single equivalent current dipole model (Hämäläinen 1993). An anatomic reference frame was established using a digital sensor position indicator. Receivers were used to triangulate the signal from the indicator placed at fiducial reference points on the subject’s head surface, such as the nasion, left and right preauricular points. These points were used to define the MEG reference frame in which the source localization was described. Radiological identification of these fiducials on high resolution MRI allowed for the transformation of MEG space into the anatomic (MRI) coordinate system and the anatomical registration of the MEG sources. The computed dipoles were co-registered to individual subjects’ MR images (3-dimensional SPGR sequence, TR/TE/Flip angle $= 35$ ms/6 ms/30°, 1-mm spatial resolution) to determine their location in an anatomic context.

**RESULTS**

*fMRI*

Unilateral and bilateral stimulation of the hand resulted in significant activation in 3 separate locations on the upper bank of the Sylvian fissure in all subjects (Fig. 2). Results are reported for the hemisphere contralateral to unilateral stimulation unless otherwise indicated. A large central focus (Fig. 2, A and B, green arrow) was consistently activated under both stimulus conditions and corresponds to S2 and PV. The Talairach coordinates of S2 and PV in the present study (Table 2), conform to those in a previous study in which the topographic organization of these fields was described in detail (Disbrow et al. 2000), S2 and PV each contain complete representations of the body’s surface that are organized as mirror symmetric maps, joined at the representations of the hands, feet, and face (Fig. 1). Thus although two separate cortical fields are located in this region, only one focus of activation can be discerned in response to stimulation of the hand. For this reason, we refer to these two fields in this study as S2/PV.

Stimulation of the hand resulted in activation in two additional locations in the lateral sulcus that have been previously described in humans (Fig. 2B). An area rostral to PV termed the rostral lateral area (RL; Fig. 2, A and B, rostral gray arrow) was activated in 7 of the 12 subjects in each of the stimulus conditions (Table 1). A third focus, caudal to S2 was in the location of 7b (Fig. 2B, caudal gray arrow). 7b was activated in...
2 of 12 subjects in the unilateral stimulus condition and 5 of 12 subjects in the bilateral condition. The locations of the centroids of activation were not significantly different for the two conditions. The mean Talairach coordinates of the hand representations for S2 and PV, RL, and 7b are listed in Table 2, and conform to those described in a previous study of these regions (Disbrow et al. 2000).

Comparisons of the extent of activation for the uni- and bilateral stimulation conditions were made for S2 and PV, RL, and 7b. In S2 and PV, there was an increase in the extent of activation during bilateral stimulation, while such an increase was not observed for areas RL and 7b (i.e., Fig. 2C). The mean number of active voxels for the bilateral stimulus condition was almost twice the number active in the unilateral stimulus condition (461 vs. 731, respectively, mean ± SD; P < 0.05; Fig. 3). There was no significant difference for univsersal bilateral stimulation in the number of active voxels for RL (37.9 ± 29.8 vs. 41.0 ± 48.2) or 7b (23.1 ± 41.7 vs. 20.7 ± 44.9; Fig. 3). However, the sample size was quite small (Table 1), and individual difference, or between subject variance, was large.

A thorough examination of ipsilateral activation was not made because half of the subjects were scanned with a surface coil, which does not allow for clear images of the entire brain. Of the six subjects scanned with a whole head coil, three showed bilateral activation of S2 and PV in response to uni-

<table>
<thead>
<tr>
<th>Subject</th>
<th>Unilateral</th>
<th>Bilateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RL S2/PV 7b</td>
<td>RL S2/PV 7b</td>
</tr>
<tr>
<td>DMS</td>
<td>X X X</td>
<td>X X X</td>
</tr>
<tr>
<td>SB</td>
<td>X X X</td>
<td>X</td>
</tr>
<tr>
<td>LM</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>PF</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>TB</td>
<td>X X X</td>
<td>X X</td>
</tr>
<tr>
<td>LK</td>
<td>X X X</td>
<td>X X</td>
</tr>
<tr>
<td>HR</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>RT</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>VC</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>PS</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>SS</td>
<td>X X</td>
<td>X X</td>
</tr>
<tr>
<td>KA</td>
<td>X X</td>
<td>X</td>
</tr>
<tr>
<td>Total</td>
<td>8/12 12/12 2/12</td>
<td>8/12 12/12 5/12</td>
</tr>
</tbody>
</table>

fMRI, functional magnetic resonance imaging; RL, rostral lateral area; S2, second somatosensory area; PV, parietal ventral area. X, significant activation in the indicated region.

MEG

The MEG response to tactile stimulation had several components (Fig. 4). First, for both uni- and bilateral stimulation a large, early peak at 40 ms was localized to the postcentral gyrus in all subjects (Fig. 5A). This peak has been well described previously and is probably due to the activity of neurons in areas 3b and 1 (Hari et al. 1993). Because there was no difference in latency or 95% confidence volume for uni- versus bilateral stimulation, the data for these variables from the two conditions are reported together. The mean latency of the S1 peak was 42.8 ± 10.2 ms. The magnetic sources were well localized with a mean 95% confidence volume of 0.19 ± 0.18 cm³ and a mean correlation of 0.98 ± 0.01.

A second component was a middle peak, occurring between 80 and 160 ms (mean = 87.8 ± 13.7 ms), localized to the upper bank of the Sylvian fissure for both stimulus conditions in all subjects (Figs. 4 and 5B). This peak is typically considered to arise from “S2” (Elbert et al. 1995; Hari et al. 1984, 1993), although distinctions between the various cortical fields residing in this region have not been made using MEG. The variance in our data was well accounted for using a single dipole (mean correlation = 0.98 ± 0.01). Thus we detected a single source at the initial S2 peak. This peak was well localized, with a mean 95% confidence volume of 0.1 ± 0.1 cm³. Further, since our fMRI results indicate that S2/PV are consistently active to tactile stimulation while RL and 7b are not,
the location of this second peak of activation in the Sylvian fissure is likely to be in S2 and PV. The initial S2/PV peak was located inferior to the S1 peak by an average of 1.5 ± 1.1 cm. This difference was significant (P < 0.01). There were no significant differences in location for the anterior-posterior or medial-lateral planes. The location in the medial-lateral plane was quite variable across subjects (SD = 1.5 cm).

A third component to the MEG response was the two to three late peaks occurring between 250 and 420 ms that also localized to the upper bank of the Sylvian fissure (Figs. 4 and 5). In 2 of the 12 subjects, no late peaks were distinguished. Thus the data on the late peaks are reported for the remaining 10 subjects. Late peaks were observed under both stimulus conditions for these 10 subjects.

In the majority of subjects (8 of 10), there were three peaks between 250 and 420 ms (i.e., Fig. 4, box) however, in 2 of the 10 subjects, there were only two late peaks (not shown). The most robust of these responses was the second peak, which showed a dipole fit correlation of over 0.97 in all subjects for both stimulus conditions. The mean latency of the second of these peaks was 390.6 ± 27.3 ms. A single source was identified (mean correlation = 0.98 ± 0.01) with a slightly larger 95% confidence volume (mean = 1.7 ± 1.3 cm³). There were no differences in location of the late peaks from each other or from the initial S2 peak.

A comparison of magnetic field strength between stimulus conditions indicated that there was no significant difference for the early component (40 ms) localized to S1 or the middle component (80 –160 ms) localized to S2. However, the magnetic field strength for the second peak of the late component (mean latency = 390.6 ms) was significantly larger for bilateral (mean RMS = 43.7 ± 33.6) versus unilateral (mean RMS = 30.1 ± 23.2) stimulation (P < 0.01; Fig. 4, arrows and Fig. 6). No comparisons were made for the first and third peaks because a robust dipole fit (correlation >0.97) was not obtained for these peaks for unilateral stimulation in several cases (4/10).

**DISCUSSION**

Our results demonstrate an increase in the extent of activation on the upper bank of the Sylvian fissure in humans, for bilateral versus unilateral stimulation of the hand, observed using fMRI and MEG. fMRI reveals an increased number of voxels in S2/PV for bilateral versus unilateral stimulation. Activation in areas RL and 7b was less consistent (Table 1). This inconsistency is in agreement with our previous work on this region (Disbrow et al. 1999, 2000) and may be due, in part, to the stimulus used. Neurons in RL and 7b may not respond optimally to simple somatosensory stimuli, but may prefer more complex or even multimodal stimuli.

In the temporal domain, the early responses at 40 ms (S1) and 80–160 ms (S2/PV), were not significantly different for
uni- versus bilateral stimulation, as measured using MEG. However, the magnitude of the late response (390.6 ms) was larger for bilateral versus unilateral stimulation. This late response was localized to the upper bank of the Sylvian fissure, the site of S2 and PV, where the existence of cells with bilateral receptive fields has been previously demonstrated in other primates (e.g., Robinson and Burton 1980a,b; Whitsett et al. 1969).

While previous work supports the idea that bilateral integration takes place in the somatosensory cortex on the upper bank of the Sylvian fissure, there is little agreement about the timing or the amplitude of the effect. Okajima et al. (1991) measured somatosensory evoked fields (SEFs) after electrical median nerve stimulation, comparing activation from bilateral stimulation to the sum of the SEFs from independent right and left median nerve stimulation. They saw no differences in amplitude of the early peaks (0–45 ms). However, significant interaction between the two waves occurred at the later peaks (57, 127, 223, and 364 ms). Simões and Hari (1999) also showed that input from both hands interacts in the S2 region. However, they did not present bilateral stimulation simultaneously, but staggered it by 300 ms. As in the present study Shimojo et al. (1997) observed no significant differences in the early (<50 ms) response for uni- versus bilateral stimulation of the tibial nerves. However, they found a decrease in the magnitude of the 80–90-ms peak, which localized to the upper bank of the lateral sulcus. No data on the late component were reported.

These differences between studies may be due in part to two factors, the length of the inter-stimulus interval (ISI) and the type of the stimulus. It has been shown (Hari et al. 1993, Kekoni et al. 1992) that the length of the ISI is positively correlated with the intensity of the signal localized to the S2 region (presumably our S2/PV), with no plateau in this effect for an ISI of =8 s. The studies described above were done with relatively short ISIs (≤2 s) (Okajima et al. 1991; Shimojo et al. 1996; Simões and Hari 1999). We balanced practicality with previous findings (Hari et al. 1993; Kekoni et al. 1992), and used an ISI of 4 s. Discrepancies may also be due to the different types of stimuli used. In the previous work described in the preceding text, electrical stimulation of a nerve was used. In contrast, we used a tactile mechanical stimulus of calibrated indentations of the skin of the fingertips. Electrical stimulation stimulates all local receptors (or primary afferents) while tactile stimulation is more specific, which may affect the amplitude of the resulting activation. In addition, the conduction velocity for electrical stimulation is shorter than for natural tactile stimuli (Forss et al. 1994), which will affect the latency of activation.

Factors underlying differential activity for unilateral and bilateral stimulus conditions

Several inferences about the organization of somatosensory cortex can be made based on the observed fMRI and MEG signal changes in the Sylvian fissure. First, the increase in the number of active voxels and magnetic field strength may reflect an increase in the number of active neurons. In fMRI, the blood-oxygenation-level-dependent (BOLD) signal is an indirect measure of neural activity derived from changes in local oxyhemoglobin concentration associated with neural metabolism. More specifically, this technique is thought to measure changes in oxyhemoglobin related to presynaptic glucose metabolism. It has been proposed that both excitation and inhibition increase this glucose metabolism (for review, see Jueptner and Weiller 1995). Thus an increase in the number of active voxels may represent an increase in the number of excitatory and/or inhibitory postsynaptic potentials (EPSPs and IPSPs, respectively). This increase may relate to an increase in the number of active presynaptic neurons. Postsynaptically, an increase in IPSPs is more difficult to interpret because it could lead to a decrease in active neurons (inhibition) or a net increase in active neurons (dissipation).

The evoked magnetic field measured using MEG arises from the synchronous activation of a population of neurons. It has been proposed that current flow in a large group of parallel dendrites, due to an influx or outflow of ions, results in a detectable evoked magnetic field (for review, see Gallen et al. 1995). The size of the group of dendrites would determine the strength of the evoked magnetic field. Therefore an increase in the MEG signal is consistent with an increase in the number of active presynaptic neurons (Fig. 7D). In fact, an increase in fMRI voxel count and MEG-evoked magnetic field have been shown in primary somatosensory cortex in response to an
increasing number of stimulated digits, and thus presumably to an increase in the number of active neurons (Roberts et al. 2000).

Several possible cortical substrates for an increase in the number of neurons responding to bilateral stimulation are suggested based on previous work in humans and other mammals. First it is possible that neurons with bilateral receptive fields require bilateral stimulation to be activated. However, although the majority of neurons in the S2 region have bilateral receptive fields, it is most likely that neurons with bilateral receptive fields would be active under both unilateral and bilateral stimulus conditions (see following text). Another possibility is that there may be neurons with entirely ipsilateral receptive fields. Results from monkey electrophysiological recording experiments suggest that a small number of neurons with exclusively ipsilateral receptive fields are present in this region (Robinson and Burton 1980b; Taoka et al. 1998). Bilateral neural responses in S2 to unilateral stimulation have been reported previously using fMRI and MEG (i.e., Disbrow et al. 2000; Hari et al. 1993), leaving open the possibility that cells with ipsilateral receptive fields exist in humans as well.

The second explanation for the increase in signal in S2/PV in response to bilateral stimulation is that there may be an increase in the firing rate of neurons under bilateral stimulus conditions (Fig. 7E). While neurons with bilateral receptive fields respond when a portion of the receptive field has been stimulated, in this case one hand, their rate of firing may increase when a larger portion of the receptive field is stimulated (i.e., both hands). Picard et al. (1990) have demonstrated this phenomenon in S2 of the cat. An increase in the rate of PSPs would increase the metabolic rate and yield a greater number of significantly active voxels. Although oxygen metabolism is thought to increase with increased firing rate, it is interesting to note that there was no difference in BOLD percent signal change for the uni- versus bilateral stimulus conditions. For MEG, an increase in rate of PSPs might also result in an evoked magnetic field with an increased amplitude (Fig. 7E).

Finally, for MEG, an increase in the synchrony of neuronal activity would result in an increase in signal intensity (Fig. 7F). Noncoherent dendritic current flow from a population of neurons would result in a decrease in the evoked magnetic field at any given time. Further, uncorrelated neural events could produce a situation in which nonsumming magnetic fields cancel each other out. Thus increasing temporal contiguity of PSPs would increase magnetic field strength. On the other hand, because fMRI is less temporally sensitive (20-s periods of stimulation), synchrony of neural activity is probably not a significant contributing factor to the extent of the BOLD signal.

These explanations of the number versus rate versus synchrony of neural firing are not mutually exclusive. Rather it is likely that the spatial and temporal differences observed under bilateral and unilateral stimulus conditions are due to a complex interaction between the number of active neurons and the rate at which they fire.

Hierarchical processing in the somatosensory cortex of primates

The MEG data presented here are consistent with the hypothesis that processing in the human somatosensory system is, to some extent, hierarchical. We observed a peak at 40 ms in S1, followed by a peak at 80–100 ms in S2/PV. Not until 300- to 400-ms post stimulus did we see differential activation for uni- versus bilateral stimulation. This temporal pattern of activation suggests that tactile inputs are first processed contralaterally in S1 (40 ms), then contrateraterally in S2/PV (80–100 ms), and then bilaterally in S2/PV (300–400 ms).

There are several lines of evidence in nonhuman primates that indicate that sensory information is processed both in parallel and in series (e.g., Grafton et al. 1990; Nicolelis et al. 1998; Pons et al. 1987; see Bullier and Nowak 1995; Pons et al. 1992 for review). While studies of connections indicate that all cortical areas receive thalamic inputs, and therefore have access to information from the sensory epithelium (see Jones 1985), lesion studies indicate that cortical inputs from primary areas to higher order cortical fields are necessary for driving the neurons within those fields. For instance, lesions to the primary visual area, V1, result in a loss of driven neural activity in extrastriate areas such as the second visual area, V2 (Girard and Bullier 1989), and the middle temporal visual area, MT (Kaas and Krubitzer 1992). In the somatosensory system of primates, lesions to 3a, 3b, 1, and 2 result in a loss of input to S2 from the body part representation that was lesioned (Grafton et al. 1990; Pons et al. 1987), and a filling in of adjacent body part representations.

In humans, existing evoked potential and MEG data are also consistent with hierarchical processing. For instance, previous studies demonstrated that activity in S1 largely precedes activity in the S2 region (e.g., Elbert et al. 1995; Hari et al. 1984, 1993), and late responses to somatosensory stimulation, ~300 ms, have been reported by other laboratories (Desmedt et al. 1977; Kekoni et al. 1992; Korvenoja et al. 1995; Okajima et al. 1991). Because the differential activation for uni- versus bilateral stimulation described in the present investigation was quite late (250- to 420-ms post stimulus), these data suggest the presence of a multisynaptic circuit.

Both there are direct connections between “S1” and S2/PV in monkeys (e.g., Burton et al. 1995; Friedman et al. 1986; Krubitzer and Kaas 1990), our MEG data suggest that a number of intermediate steps in processing may take place in other regions of cortex before inputs from both hands interact in S2/PV via connections from the opposite hemisphere. The anatomical substrate for extensive intrahemispheric processing has been well described in a number of studies of nonhuman primates (e.g., Jones and Powell 1969a; see Kaas and Pons 1988 for review). For instance, interconnections between anterior parietal fields 3a, 3b, 1, and 2 have been described as well as connections between anterior parietal fields and somatosensory fields in posterior parietal cortex and the lateral sulcus (the Sylvian fissure in humans). In monkeys, the representation of the hand in areas 3a and 3b is acallosal (e.g., Jones and Powell 1969b; Karol and Pandya 1971; Killackey et al. 1983; Shanks et al. 1985), and in areas 1 and 2, is almost completely acallosal (Killackey et al. 1983). Thus the site of integration of inputs between the hands must occur elsewhere in cortex. S2/PV is a viable candidate for the site of bimanual integration because patchy callosal connections have been observed throughout S2, including the representation of the hand (Karol and Pandya 1971; Krubitzer and Kaas 1990; Manzoni et al. 1984).

Taken together, the present results support the idea that there
are common features of somatosensory processing that all primates share. First, areas in the Sylvian fissure including S2 and PV are involved in processing bilateral inputs from the hands. Second, at least in part, tactile inputs are processed serially in somatosensory cortex from “S1” to S2/PV. Third, there may be extensive intrahemispheric processing of somatic inputs to the hand before information is sent to the opposite hemisphere. Finally, bilateral integration is encoded in three potential ways: increased number of neurons firing, increased rate of firing, and/or increased synchrony of firing.

The authors thank S. Honma, P. Ferrari, and G. Cicerelo for technical assistance, G. Recanzone for helpful discussion, K. Huffman for review of the manuscript, and K. Britten for technical support. We also thank S. Brown for drawing Fig. 1.

This work was supported by National Institute of Neurological Disorders and Stroke Grant R01-NS-35103-01A1 and Whitbread Foundation Grant M97-20 to L. Krubitzer, a McDonnell-Pew Foundation grant to L. Krubitzer and E. Disbrow, and a UCSD Radiology Pilot Research program award to E. Disbrow and T. Roberts.

REFERENCES


GARRAGHTY PE, PONS TP, AND KAAS JH. Ablations of areas 3b (SI proper) and 3a of somatosensory cortex in marmosets deactivate the second and parietal ventral somatosensory areas. Somatosens Mot Res 7: 125–135, 1990.


