NeuroReport 7, 2849–2852 (1996)

Functional MR imaging of the human sensorimotor cortex during haptic discrimination

Jean-Luc Anton,[1] Habib Benali,[2] Emmanuel Guigon,[1,3,CA] Mireille Di Paola,[4] Jacques Bittoun,[5] Odile Jolivet[5] and Yves Burnod[1]

[1]INSERM CREARE, U.P.M.C., Boîte 23, 9, quai Saint-Bernard, 75005 Paris Cedex 05; [2]INSERM U66, CHU Pitié Salpêtrière, 75634 Paris; [3]CNRS URA 1488, Institut des Neurosciences, Paris; [4]IGR, 94800 Villejuif; [5]CIERM, CNRS URA 2212, 94275 Le Kremlin Bicêtre, France

[CA,1]Corresponding Author and Address

THIS study attempted to determine whether haptic discriminations of shape (haptic task) activate the same tissue in the central cortical region of normal human subjects as do finger movements (opposition task). Opposition and haptic tasks both activated the central sulcus, as expected from previous imaging studies. The haptic task activated about 50% of the cortical territory activated by the opposition task. The results suggest that exploratory digital movements performed to collect precise somatosensory information and automatic movements performed during finger positioning activate partially overlapping parts of the sensorimotor cortex.

Key words: Finger movement; fMRI; Haptic discrimination; Human

Introduction

Révész[1] recognized a specific mode of touch called haptics or active touch, which cannot be reduced to a simple combination of touch and kinaesthesia.[2] Active touch involves exploratory movements which extract information on the surface of an object by adjusting the receptive surface for detecting and registering the properties of the object.[3] The issue of the central representation of haptic processing in human brain was addressed recently by O'Sullivan *et al*[4] who used positron emission tomography (PET) to compare the brain activations induced by an object length discrimination task and a control somatomotor task designed to reproduce finger movements performed in the discrimination task. The length task activated a region in the anterior part of the contralateral postcentral gyrus, as well as the banks of the postcentral sulcus. These results suggest that the participation of primary sensorimotor cortex in haptic processing is not reduced to the control of finger movements or finger positioning. We used functional magnetic resonance imaging (fMRI), which provides a high resolution measure of local haemodynamic changes in the human brain during a given behaviour,[5,6] to determine the patterns of activation induced by finger opposition movements and haptic discrimination in the primary sensorimotor cortex. The issue is whether these tasks share common activation foci, or activate separate or partially overlapping cortical fields.

Materials and Methods

Behavioural tasks: The study was performed on 17 right-handed human subjects, all of whom were healthy, had no known neurological problems and gave their informed consent following the guidelines of the Human Studies Committee of Hôpital de Bicêtre. The subjects performed two tasks, using their right hand. The opposition task consisted of repetitive self-paced movements of the fingers in opposition to the thumb. A set of 100 three-dimensional wooden objects was used for the haptic task. Ten different objects were used. Prior to image acquisition, subjects were given one object (sample) and were asked to memorize it. During acquisition, subjects were asked to compare a series of objects to the sample and to classify them as match or mismatch. The subjects were not able to visualize the objects.

Image acquisition: MR images were acquired with a standard 1.5T Signa MR imaging system (General Electric Medical Systems) with a standard head coil. Frontal MR images were acquired around the central sulcus. A sagittal medial anatomical image was used to find the intercommissural line in order to detect the somatomotor hand area. Two or three contiguous frontal sections were selected (eight and nine subjects, respectively). The following images were acquired at each section (field of view, 24 cm; size 128 × 256; pixel size, 1.88 × 0.94 mm, slice thickness, 5 mm): frontal anatomical image (spin echo T1-weighted, TR = 500 ms, TE = 11 ms); angiography image (gradient echo sequence, TR = 45 ms, TE = 13 ms, flip angle = 60°) to detect the main veins; functional images (gradient echo sequence, TR = 80 ms, TE = 60 ms, flip angle = 20°) during the two behavioural conditions and rest. Three sets of five images were acquired for each condition (image acquisition time, 20.5 s).

Data processing: The sequence of the functional images was first processed to compensate for the inter-frame motion due to small movements of the head and the brain. Since the slices were thick (5 mm) and the amplitude of motion was small (~2 mm), we assumed that the displacement occurred in the acquisition plane. The parameters of planar translation and rotation were estimated by maximizing the correlation coefficient between a reference image and other images in a series.[7] The images were then analysed using conditioned analysis.[7] For this, the images of one condition were projected on to the vectorial subspace orthogonal to the image space of the other condition. We noted n the number of pixels in images ($n = 256 \times 256$), p the number of images for each condition ($p = 15$), and A (resp. B) the $n \times p$ matrix which contains the p measures of each pixel for one task (resp. rest). The conditioned data set D ($n \times p$ matrix) was obtained by $D = Q_B A$, where $Q_B = I - B(BB^t)^{-1}B^t$ is the orthogonal projector on the vectorial subspace orthogonal to B, and I is the $n \times n$ identity matrix. The conditioned data set represents the part of the signal in A (task) which is not correlated with the signal in B (rest). This method gives an estimate of the relevant difference between the signals in two conditions, free of noise and any unrelated artefactual signal.

Principal component analysis was performed on the conditioned data set D. The statistical map for comparing the two conditions was defined as the normalized first principal component. Principal components associated with other eigenvalues were not used, since most of the variance was explained by the first principal component. The distribution of values in the statistical maps was Gaussian and depended on the size of the functional images and not on the number of images.[7] The values of the statistics rather than the underlying signal variations were used in the following analysis.

Thresholding with hysteresis was applied to the statistical maps.[8] Any pixel above an upper threshold ($\Theta_H = 3.09$, $p = 0.001$) was defined as a source pixel. A growing process was then applied to each source pixel to generate compact zones of at least eight adjoining pixels above a lower threshold ($\Theta_L = 1.28$, $p = 0.1$). The resulting images were made up of multiple clusters of activated pixels. As previously observed, the highest values in the statistical maps were at the location of the main veins detected on MR angiograms.[9,10] A threshold ($\Theta_A = 4$, $p = 0.00003$) was used to separate the highest value pixels from the other activated pixels. These other pixels were used as a measure of task-induced changes in neural activity.

The anatomical limits of the central sulcus region (CS) were determined for each subject. The activation in the CS was defined as the number of pixels which belonged to clusters whose source pixels were in this region.

Results

There was functional activity in the contralateral CS during performance of both tasks. Figure 1 shows the functional activity during the two tasks for a representative subject. The region of the contralateral CS was active in both conditions. The haptic task also activated the contralateral postcentral sulcus (Fig. 1B). There was activation in 27 of 43 sections during the opposition task, and in 32 of 43 sections during the haptic task. The spatial extent of activation varied among subjects and tasks, from 0 to 284 pixels. The mean spatial extent over non-zero activations was 68 ± 64 pixels for the opposition task and 89 ± 58 pixels for the haptic task. The mean signal increase over selected pixels was 9.4% for the opposition task and 10% for the haptic task.

The results were then analysed to determine whether the opposition and haptic tasks activated CS in the same manner. The large inter-individual variations, however, prevented the mean spatial extent of activation for all the subjects being used as a characteristic of functional activity. The distributions of the pixels activated in the two tasks were compared. Haptic activations generally involved more pixels than opposition activation (Fig. 2). The spatial extent of the overlap between activations (opposition$\cap$haptic) was calculated as the number of pixels significantly activated during the two tasks. There was a linear relationship between opposition activation and its overlap with haptic activation (Fig. 2; $y = 0.53x - 4.05$; $r = 0.942$; $n = 21$). The confidence intervals for slope and offset were [0.44;0.61] and [−12.3;4.2] ($p = 0.05$). Hence, a constant proportion of opposition pixels were also active during the haptic task, suggesting that the opposition and haptic tasks activated two partially overlapping regions.

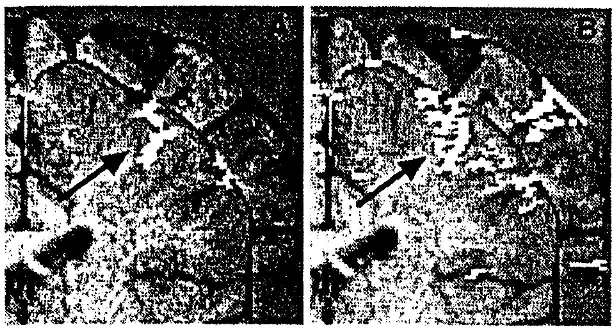

FIG. 1. Activation maps superimposed on a T1-weighted anatomical image for one subject. Two adjacent sections are shown. (**A**) Opposition task. (**B**) Haptic task. Arrows indicate the central sulcus activation.

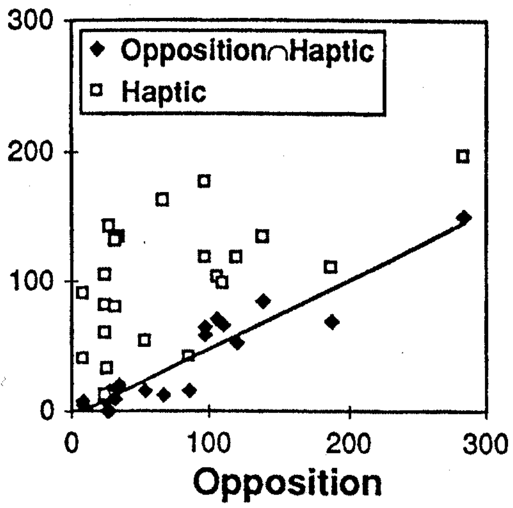

FIG. 2. The extent of activations in the central sulcus region (CS) (in number of pixels) during opposition and haptic tasks. For each brain section, the horizontal axis indicates the number of pixels during the opposition task in the contralateral CS, and the vertical axis indicates the number of pixels during the haptic task (square) and the number of pixels in opposition∩haptic (diamond) in the contralateral CS. The points corresponding to a null spatial extent on either axis were removed. The regression line corresponds to opposition∩haptic = *a*opposition + *b*.

The mean signal variations in overlapping and non-overlapping areas over all subjects were not statistically different (two-tailed *t*-test, $p > 0.1$ for all sections in the two tasks). Increasing the lower statistical threshold (Θ_L; see Materials and Methods) did not change markedly the estimate of the overlap, although the uncertainty on its value increased (Fig. 3). These results indicate that we obtained a robust measure of the overlap between opposition and haptic activations.

Discussion

The goal of this study was to determine whether haptic discriminations of shape activate the same tissue as finger movements in the sensorimotor cortex of normal human subjects. The opposition and haptic tasks activated the CS, as expected from previous imaging studies.[4,11,12] The two tasks also activated partially overlapping parts of the sensorimotor cortex. The haptic task activated about 50% of the cortical territory activated by the opposition task.

There are three difficulties in interpreting these results. First, two or three slices provide a partial view of the sensorimotor cortex. Parts of this region may have been incompletely visualized. The use of a multislice echo-planar imaging (EPI) system could give a more precise information on the activated volume.[13] EPI, however, has in general a low spatial resolution (voxels of ~50 mm^3) and would provide less accurate estimates of the size of overlapping territories. The robustness of our results (Fig. 3) suggests that our methodology based on gradient echo imaging provided with accurate measures of overlaps. Second, the subjects may not have executed the tasks in the same way (frequency of movement, number of explored objects, number of errors), which could perturb the inter-subject analysis.[14] The main point is that the activations were not compared between subjects, but between tasks for each subject.[15] What is actually compared is the relative representation of two tasks belonging to different sensorimotor repertoires (see below; Ref. 16) rather than the performance of these tasks. Third, the changes in contrast measured by fMRI during activation is due to changes in blood flow velocity in capillaries and larger vessels,[9,10] and to BOLD effect concentrated both in large vessels and in active tissue.[17] Inflow effects were minimized in our study by using of a long TR (80 ms) and a low flip angle (20°).[18] The BOLD effect in large vessels may be predominant in gradient-echo imaging at 1.5T.[19] The validity of the analysis of overlaps between task-induced activations relies on the assumption that the signals in overlapping and non-overlapping areas are similar. There was no statistically significant difference between the mean signal variations in overlaps and non-overlaps. Furthermore, the growing process had little influence on the size of the overlap, indicating that the relative sizes of overlaps and non-overlaps remained constant over a large range of thresholds. The results thus suggest that there is a true, measurable overlap between the task-induced activations, that may reflect the functional components of the behavioural tasks examined.

The activations were measured in the banks of the CS which contain parts of cytoarchitectonic areas 1/3b, 3a, 4p and 4a.[20,21] In non-human primates, these areas contain a separate body representation and process different components of somatic sensation and motor output.[22,23] The overlap between opposition and haptic activations can be readily correlated

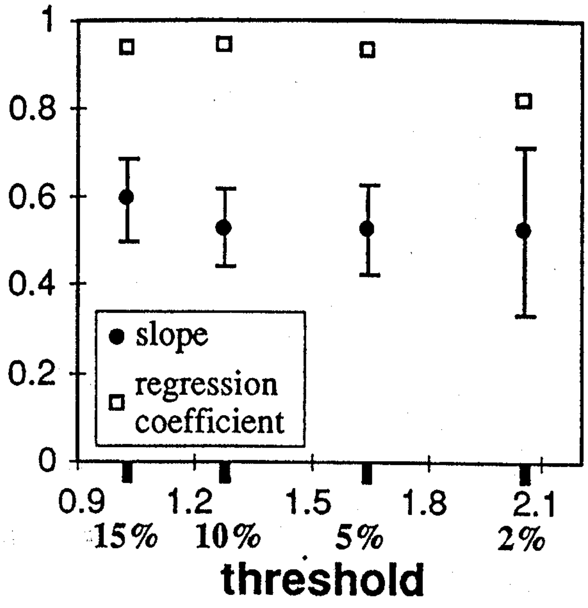

FIG. 3. Changes in the relative size of the overlap between opposition and haptic activations with statistical threshold. The horizontal axis indicates the lower statistical threshold Θ_L. The probability associated with the tested threshold values is indicated. The vertical axis indicates the slope a (circle) of the regression line $\text{opposition} \cap \text{haptic} = a\,\text{opposition} + b$, and the correlation coefficient of the regression (square). 5% confidence intervals of a are indicated.

with common motor, proprioceptive and cutaneous signal processing in these cortical areas during the two tasks. The pure haptic activation might be linked to a specific component responsible for the integration of tactile and proprioceptive information to recover the shape of the manipulated object. O'Sullivan *et al*[4] observed a similar activation in the anterior part of the postcentral gyrus when comparing the tactile discrimination of shapes and finger movements.

The existence of a pure opposition activation, although surprising, is not unexpected. Different types of sensorimotor control may be involved in automatic finger movements (motor skills) and exploratory digital movements aimed at collecting precise somatosensory information.[16] Different patterns of movement-related tactile activity may result from predictable contacts between fingers during opposition movements and unpredictable contacts with the object during exploratory movements. A possible cortical correlate of these observations may be the supraspinal component of the cutaneomuscular reflex that is specific to relatively independent finger movements and absent during prehension movements.[24]

Conclusion

Mapping of the human brain by fMRI at millimeter resolution can reveal robust features of the functional organization of the human primary sensorimotor cortex. Activations induced by finger opposition movements and exploratory haptic movements overlap and the area is consistent across subjects. Hence, the central representations associated with the sensorimotor control of these two types of movements partially overlap.

References

1. Révész G. *Psychology and Art of the Blind.* New York: Longmans Green, 1950.
2. Gibson JJ. *Psychol Rev* **69**, 477–491 (1962).
3. Lederman SJ and Klatzky RL. *Cogn Psychol* **19**, 342–368 (1987).
4. O'Sullivan BT, Roland PE and Kawashima RA. *Eur J Neurosci* **6**, 137–148 (1994).
5. Kwong KK, Belliveau JW, Chesler DA *et al. Proc Natl Acad Sci USA* **89**, 5675–5679 (1992).
6. Ogawa S, Tank DW, Menon R *et al. Proc Natl Acad Sci USA* **89**, 5951–5955 (1992).
7. Benali H, Anton J-L, Di Paola M *et al.* Conditioned statistical model for functional MRI studies of the human brain. In: Bizais Y, Di Paola R and Barillot C, eds. *Information Processing in Medical Imaging.* Dordretch: Kluwer Academic Publishers, 1995: 311–322.
8. Canny JF. *I.E.E.E. Trans Pattern Analysis Machine Intelligence* **8**, 679–698 (1986).
9. Lai S, Hopkins AL, Maacke EM *et al. Magn Reson Med* **30**, 387–392 (1993).
10. Segebarth C, Belle V, Delon C *et al. NeuroReport* **5**, 813–816 (1994).
11. Kim SG, Ashe J, Georgopoulos AP *et al. J Neurophysiol* **69**, 297–302 (1993).
12. Boecker H, Khorram-Sefat D, Kleinschmidt A *et al. Hum Brain Mapp* **3**, 236–244 (1995).
13. Sanes JR, Donoghue JP, Thangaraj V *et al. Science* **268**, 1775–1777 (1995).
14. Schlaug G, Sanes JR, Thangaraj V *et al. NeuroReport* **7**, 879–883 (1996).
15. A, Meyer G, Jezzard P *et al. Nature* **377**, 155–158 (1995).
16. Kunesch E, Binkofski F and Freund H-J. *Exp Brain Res* **78**, 539–546 (1989).
17. Ogawa S, Lee T-M, Kay AR *et al. Proc Natl Acad Sci USA* **87**, 9868–9872 (1990).
18. Frahm J, Merboldt KD, Hanicke W *et al. NMR Biomed* **7**, 45–53 (1994).
19. Haacke EM, Hopkins A, Lai S *et al. NMR Biomed* **7**, 54–62 (1994).
20. Geyer S, Zilles K, Simon U *et al. Hum Brain Mapp* **1 (Suppl.)**, 290 (1995).
21. Simon U, Geyer S, Zilles K *et al. Hum Brain Mapp* **1 (Suppl.)**, 259 (1995).
22. Tanji J and Wise SP. *J Neurophysiol* **45**, 467–481 (1981).
23. Kaas JH. *Physiol Rev* **63**, 206–231 (1983).
24. Evans AL, Harrison LM and Stephens JA. *J Physiol (Lond)* **418**, 1–12 (1989).

ACKNOWLEDGMENTS: We thank P. Baraduc, A. Berthoz, P. Buser, R. Caminiti, R. Carlier, E. Koechlin, J.-C. Saucet and A. Roby for useful suggestions, J. Prud'homme and R. Rouxel for technical help, O. Parkes for editing the English text. J.L.A. was supported by a grant from IFSBM.

Received 15 July 1996;
accepted 1 August 1996

General Summary
The spatial extent and overlap of functional magnetic resonance imaging (fMRI) signals induced in the human cortical sensorimotor hand area by finger opposition movements (opposition task) and tactile object discriminations (haptic task) were analysed. Both tasks consistently activated the contralateral central sulcus region and the areas activated partly overlapped. The haptic task activated about 50% of the cortical territory activated by the opposition task. This suggests that common and specific neuronal populations are involved in different components of these tasks.