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Neural networks for Braille reading by the blind

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Summary

To explore the neural networks used for Braille reading, we measured regional cerebral blood flow with PET during tactile tasks performed both by Braille readers blinded early in life and by sighted subjects. Eight proficient Braille readers were studied during Braille reading with both right and left index fingers. Eight-character, non-contracted Braille-letter strings were used, and subjects were asked to discriminate between words and non-words. To compare the behaviour of the brain of the blind and the sighted directly, non-Braille tactile tasks were performed by six different blind subjects and 10 sighted control subjects using the right index finger. The tasks included a non-discrimination task and three discrimination tasks (angle, width and character). Irrespective of reading finger (right or left), Braille reading by the blind activated the inferior parietal lobule, primary visual cortex, superior occipital gyri, fusiform gyri, ventral premotor area, superior parietal lobule, cerebellum and primary sensorimotor area bilaterally, also the right dorsal premotor cortex, right middle occipital gyrus and right prefrontal area. During non-Braille discrimination tasks, in blind subjects, the ventral occipital regions, including the primary visual cortex and fusiform gyri bilaterally were activated while the secondary somatosensory area was deactivated. The reverse pattern was found in sighted subjects where the secondary somatosensory area was activated while the ventral occipital regions were suppressed. These findings suggest that the tactile processing pathways usually linked in the secondary somatosensory area are rerouted in blind subjects to the ventral occipital cortical regions originally reserved for visual shape discrimination.

Keywords: blind; braille; visual cortex; multimodal plasticity; PET

Abbreviations: BA = Brodmann area; rCBF = regional cerebral blood flow; SPM = statistical parametric map

Introduction

Braille reading requires the conversion of simple tactile information into meaningful patterns that have lexical and semantic properties. While the perceptual processing of Braille may be mediated by the somatosensory system, visual letter identity is routinely accomplished within the visual system. In the blind, the visual system is not used for its intended purpose and might conceivably be idle. Tactile imagery or Braille reading in blind subjects caused task-related activation in occipital leads in the EEG study of Uhl *et al*. (1991). While the site of origin of EEG potentials is uncertain, this finding suggested that somatosensory input is redirected into the occipital area. Elevated metabolic activity of the occipital cortex in humans blinded early in life suggested that it can subserve non-visual functions (Wanet-Defalque *et al*., 1988; Uhl *et al*., 1993), although no task-related activation in the occipital cortex was seen. We have previously reported activation of the primary visual cortex when the blind read Braille and carry out other tactile discrimination tasks (Sadato *et al*., 1996). Furthermore, to address the function of the primary visual cortex of the blind, we used transcranial magnetic stimulation to induce transient disruption of function of cortical areas during identification of Braille letters in the blind. Occipital stimulation induced errors in Braille reading in subjects who became blind early in life, but not in sighted subjects reading embossed Roman letters (Cohen *et al*., 1997). These findings suggest a remarkable plasticity of the brain, potentially permitting additional processing of tactile information in the visual cortical areas. Here, we report that the neural networks representing different modalities are activated during the

performance of tactile discrimination tasks by both blind and normal subjects. These results extend our previous observations, and indicate a reorganization of the network in the blind.

Subjects and methods

For the Braille-reading task, four men and four women aged 37–62 years (mean 49.6 years) were recruited. All were strongly right-handed, as assessed with the Edinburgh handedness inventory (Oldfield, 1971); six had acquired blindness and two were congenitally blind (mean age of blindness, 4.3 years). They all had normal MRI scans, and the cause of blindness did not include a progressive neurological disease. All subjects started Braille reading between the ages of 4 and 8 years, devoting 1–3 h/day to reading. The blind subjects newly recruited for the non-Braille tactile studies included four men and two women aged 28–48 years (mean 42.2 years). Five were right-handed and one was left-handed. Five had acquired blindness and one was congenitally blind (mean age of blindness, 1.5 years). All had a neurological examination and the cause of blindness did not include a progressive neurological disorder. These blind subjects started Braille reading between the ages of 4 and 6 years, spending 1–6 h/day reading. Information regarding the blindness, such as the onset, cause, duration and severity, were obtained by the investigator's interview, and were supplemented by medical records when available. All but one blind subject denied any light perception. The exception, who suffered from primary retinal degeneration which was congenital in aetiology, was virtually blind from birth and reported that he could perceive strong light very vaguely, participated in the non-Braille tactile discrimination experiments. Many of the subjects had their eyes enucleated, so light perception was not possible. The blind subjects' data are summarized in Table 1. Sighted subjects for the non-Braille tactile studies consisted of three men and seven women aged 23–45 years (mean 35 years), all right-handed. Normal vision was confirmed by neurological examination. The protocol was approved by the Institutional Review Board, and all subjects gave their written informed consent for the study.

Braille reading

The Braille reading experiment included three conditions: rest, reading (mostly) non-words and reading (mostly) words. For the resting scans, the subject lay quietly with no movement and no verbal response. For the reading scans, subjects were asked to place the index finger of one hand on a window (6.4 × 1.9 cm) where eight-character, non-contracted Braille words randomly selected from the Toronto Word Pool (Friendly *et al*., 1982) appeared every 2.4 s. Each word was presented for 1.8 s. Subjects were instructed to scan all Braille characters with their index fingers from left to right. In the 'word' condition, subjects were presented with 44 Braille letter strings, three of which were non-words (all consonant letter strings), while the other 41 were common nouns and verbs. Subjects were instructed to utter 'num' when they encountered the non-words. For real words, no response was requested. In the 'non-word' condition, three letter strings were real words whereas the other 41 letter strings were non-words. In this condition, subjects were asked to respond only when a real word was presented. Each condition began 10 s before the tracer injection and continued for the duration of the scan. The task duration was ~90 s for each condition. Each condition was performed twice with both the right and left index fingers. The order of presentation was counterbalanced within sets and across individuals. The initial and final scans of the series of 10 were done with the subject at rest. The lexical discrimination tasks were performed during the intervening eight scans.

Non-Braille tasks

The non-Braille tasks consisted of five conditions: rest, sweep, angle discrimination, width discrimination and non-Braille character discrimination. The sweep condition was a sensorimotor control task; angle and width discrimination tasks were for non-lexical tactile discrimination, and the character discrimination task was for a non-Braille lexical tactile discrimination task. In the resting condition, subjects lay quietly with neither task nor verbal response. In task conditions, subjects were asked to place their right index finger on a window (6.4 × 2.5 cm) where different patterns appeared every 5 s. Subjects were instructed to scan all patterns with their right index finger from left to right and from right to left.

In the 'sweep' condition, subjects were asked to sweep a rough surface homogeneously covered with Braille dots. In this condition, no response was required. In the angle discrimination condition, two grooves were presented in pairs. This pattern was made by cutting out the grooves from a paper homogeneously covered in Braille dots, identical to the one used in the sweep condition. The two grooves were separated by at least 6.4 mm. The width of the grooves was the same (3.2 mm) while their (independent) orientations were horizontal, vertical or oblique. Subjects were asked to respond by whispering 'num' when the angles were the same. In the width discrimination condition, two vertical grooves, separated by 6.4 mm, were presented in pairs. The width of each groove was either 3.2 or 4.6 mm. Subjects were asked to respond 'num' when the widths were the same.

In the character discrimination condition, three upper-case English letters embossed with Braille dots (12.7 mm in height and 10.2 mm in width, separated by 6.4 mm) were presented together. While the first and third characters were always the same, the middle character could differ. Subjects were asked to respond 'num' if the middle character was the same.

In each condition, 10% of the total presentations (three out of 30) were 'identical' trials. Each condition began 30 s before the tracer injection and continued for the duration of

Table 1 *Blind subjects who participated in the Braille reading and non-Braille tactile tasks tasks*

Patient	Age	Sex	Handedness	Preferred side for reading	Age at onset of blindness (years)	Cause of blindness	Braille started at (years)	Braille practice (h/day)	Enucleation of eyeballs confirmed by MRI
Blind subjects who participated in the Braille reading tasks									
1	60	M	R	R	4	CNS infection	5	3	+
2	43	M	R	R	0	Retinolental fibroplasia	5	1.5	+
3	58	M	R	L	5	CNS infection	7	1	−
4	49	F	R	R	0	Anophthalmos	6	2	(eyeball unidentified)
5	55	F	R	R	13	Retinolental fibroplasia	8	3	+
6	45	M	R	R	0	Optic nerve dysplasia	5	4	− (optic nerve unidentified)
7	45	F	R	L	0	Retinolental fibroplasia	6	1	− (atrophic eyeball)
8	42	F	R	R	12	Congenital glaucoma	5	2	+
Blind subjects participated in non-Braille tactile tasks									
1	28	M	R	R	5	Retinolental fibroplasia	5	1	NA
2	48	M	R	R	1	Glaucoma	5	2.5	− (atrophic eyeball)
3	39	F	L	L	3	Brain surgery	4	4	−
4	44	M	R	R	0	Retinolental fibroplasia	6	6	+
5	46	F	R	L	0	Retinolental fibroplasia	6	2.5	NA
6	48	M	R	L	0	Primary retinal degeneration	6	1	NA

NA = MRI not available.

the scan. The task duration was ~150 s for each condition. The latter was performed twice with the right index finger only. The order of presentation was counterbalanced within sets and across individuals. The initial and final scans of the series of 10 were done with the subject at rest. The tasks were performed during the intervening eight scans. Throughout the PET examination, both blind and sighted subjects closed their eyes which were also patched.

PET

PET scanning was performed with a Scanditronix PC 2048-15B (Uppsala, Sweden) 15-slice tomograph with an interslice spacing of 6.5 mm. Images were reconstructed to a full width at half maximum of 6.5 mm. Coverage of the cerebellum was limited to, and just above, the level of the dentate nucleus because of the limitation of the axial field of view and the need to include the supplementary motor area. Cerebral blood flow (CBF) images were obtained by integrating the activity occurring during the 60-s period following the initial increase in cerebral radioactivity after an intravenous bolus injection of 30 mCi of ^{15}O-labelled water. Tissue activity recorded by this method is linearly related to regional CBF (rCBF) (Fox *et al*., 1984; Fox and Mintun, 1989).

Analysis

The data were analysed with statistical parametric mapping (using software from the Wellcome Department of Cognitive Neurology, London, UK) implemented in Matlab (Mathworks, Sherborn, Mass., USA) (Friston *et al*., 1989, 1990, 1994, 1995). The scans from each subject were realigned using the first image as a reference. Following realignment, all images were transformed into a standard stereotaxic space (Talairach and Tournoux, 1988). After the appropriate design matrix was specified, the condition, subject and covariate effects were estimated according to the general linear model at each and every voxel. The design matrix included global activity as a confounding covariate, and this analysis can therefore be regarded as an analysis of covariance (Friston *et al*., 1990). To test hypotheses about regionally specific condition effects, the estimates were compared using linear contrasts. The resulting set of voxel values for each contrast constitutes a statistical parametric map of the t statistic SPM$\{t\}$. The SPM$\{t\}$ were transformed to the unit normal distribution (SPM$\{Z\}$). The significance of activity in each region was estimated using the distributional approximation from the theory of Gaussian fields (Friston *et al*., 1995). $P < 0.05$ of a corrected P-value was used as a statistical threshold (Friston *et al*., 1994, 1995).

To depict the foci activated by either the right or left index finger reading, all local maxima of activation in the comparisons with rest [(right – rest) and (left – rest)] with statistical significance of $P < 0.05$ with correction for multiple comparisons at voxel level were selected. Then, using the statistical threshold in each comparison, the foci were categorized into those activated by (i) both right and left finger reading, (ii) right only and (iii) left only. Significance of difference between right and left reading has been addressed *post hoc*.

To evaluate the effect of the onset of blindness, the eight blind subjects participating in the Braille reading tasks were categorized as early onset and later onset subgroups. Four of the eight blind subjects were already blind at birth, while the other four lost their sight later in their life (mean onset of their complete blindness was 8.5 years), although two of them suffered from severe visual disturbance from their birth

until their complete loss of sight. Thus, the first four were categorized as early onset blind and the other four as later onset blind. Common activation irrespective of onset of blindness was assessed by conjunction analysis (Price and Friston, 1997). With this approach, several hypotheses are tested, asking whether all the activations in a series of task pairs are jointly significant. We compared four different Braille reading tasks with rest (early or late onset blind subjects using the left or right index finger) to identify the areas which are activated by Braille reading irrespective of reading finger or onset of blindness. Differences due to onset of blindness were also assessed using a Group $\times$ Condition interaction analysis.

To assess the effect of blindness on the regional neural activities during the rest condition, two rest scans were obtained from each subject in each group (early and later onset, and sighted), and were averaged and compared across the three groups. Proportional scaling was performed to eliminate any global CBF effects. With appropriate linear contrasts, regionally specific study effects, i.e. blind versus sighted, on the rCBF were assessed at rest.

To clarify the relationship between the side of the reading finger and the areas activated by Braille reading, all the activated foci obtained as local maxima by comparing (right index finger – rest) with (left index finger – rest) were retrospectively examined to determine if they were activated by the right index finger only, left index finger only, or by both right and left (Table 3). The difference in activation by the two fingers was also assessed (right index finger – left index finger). The relationship between the preferred fingers for Braille reading and the activation in the primary sensorimotor area was examined by a region of interest analysis, since single local maxima may not best represent an anatomical region, particularly when a given task caused extensive activation as demonstrated in our particular study. Rather than defining an actual region of interest, we selected two symmetrically located coordinates which reflected the intensity around them (its extent is defined by full width half maximum). Location of the primary sensorimotor area was determined by the activation pattern from the PET data, as well as the anatomical information from the Talairach and Tournoux atlas (1998). As the coordinates of ($\pm$28, $-$22, 52) are closer to the central sulcus than ($\pm$18, $-$18, 52), based on the atlas, we chose the former for the assessment.

Results

Task performance is summarized in Table 2. There was no significant difference between the blind and the sighted subjects in the performance of non-Braille tactile discrimination tasks ($P = 0.25$, one-way analysis of variance).

Braille reading by the blind (Table 3 and Figs 1–3)

Braille reading by the blind activated several brain areas (Table 3 and Fig. 1). Regardless of the side of the reading finger, activation was present in the inferior parietal lobule, primary visual cortex, superior occipital gyri, fusiform gyri, ventral premotor cortex, superior parietal lobule, cerebellum and primary sensorimotor area bilaterally, and also the right dorsal premotor area, right middle occipital gyrus, right inferior occipital gyrus and right prefrontal area. The right primary sensorimotor area was activated more prominently by left index finger reading, whereas the left primary sensorimotor area was activated equally by either right or left finger reading. The superior parietal lobule was activated more prominently by contralateral than by ipsilateral index finger reading. With right index finger reading, additional activation was noted in the left inferior occipital gyrus, left anterior inferior parietal lobule, right dentate nucleus, dorsal portion of left primary sensorimotor area and the supplementary motor area. These areas did not show statistically significant activation during left index finger reading. With left index finger reading, the left dentate nucleus and right inferior occipital gyrus were activated while there was no statistically significant activation during right index finger reading. No significant difference was found between the reading word and non-word conditions.

The effect, in the visual cortex, of the time of onset of blindness is shown in Fig. 2. The bilateral occipital cortex, including the primary visual cortex, was consistently activated irrespective of the side of the reading finger or the timing of the onset of blindness ($P < 0.05$ with correction for multiple comparisons); there were no significant differences among these conditions. There was a non-significant tendency for more activation adjacent to the commonly activated area in the left primary visual cortex of the later onset group than the earlier one, when Braille reading was compared with rest (uncorrected $P < 0.001$). Hence, the critical point is that the primary visual cortices of both early and later blind groups are activated during Braille reading, irrespective of reading fingers.

Figure 3 shows the relationship between the preferred finger for Braille reading and activation of the primary sensorimotor area. The comparison of right and left primary sensorimotor area during a task was measured as a laterality index $[(r - l)/(r + l) \times 100)$. Six of the eight blind subjects who preferred the right index finger showed greater activation in the left primary sensorimotor area than in the right counterpart during right index finger reading. Two of these persisted with a left-sided preponderance, even with left index finger reading. The two subjects who preferred left index finger reading showed greater activation in the right primary sensorimotor area with both right and left index finger reading. Their laterality to the right with right index finger reading exceeded all but two values of laterality to the right for left index finger reading of those preferring reading with the right index finger. A two-factor analysis of variance showed that the preference effect [$F(1,12) = 22.52$, $P = 0.0005$] and reading effect [$F(1,12) = 11.7$, $P = 0.005$] were both significant, whereas their interaction was not significant [$F(1,12) = 0.47$, $P = 0.507$].

Table 2 *Task performance*

	Blind Braille (n = 8)	Blind non-Braille (n = 6)	Sighted non-Braille (n = 10)
Overall performance (% accuracy*)	95.7 ± 3.2	92.5 ± 7.9	87.1 ± 6.8
Non-word task performance (% accuracy*)	97.1 ± 2.7		
Word task performance (% accuracy*)	94.4 ± 4.0		

*% accuracy = (number of correct responses/number of presentations) × 100, presented as mean ± SD.

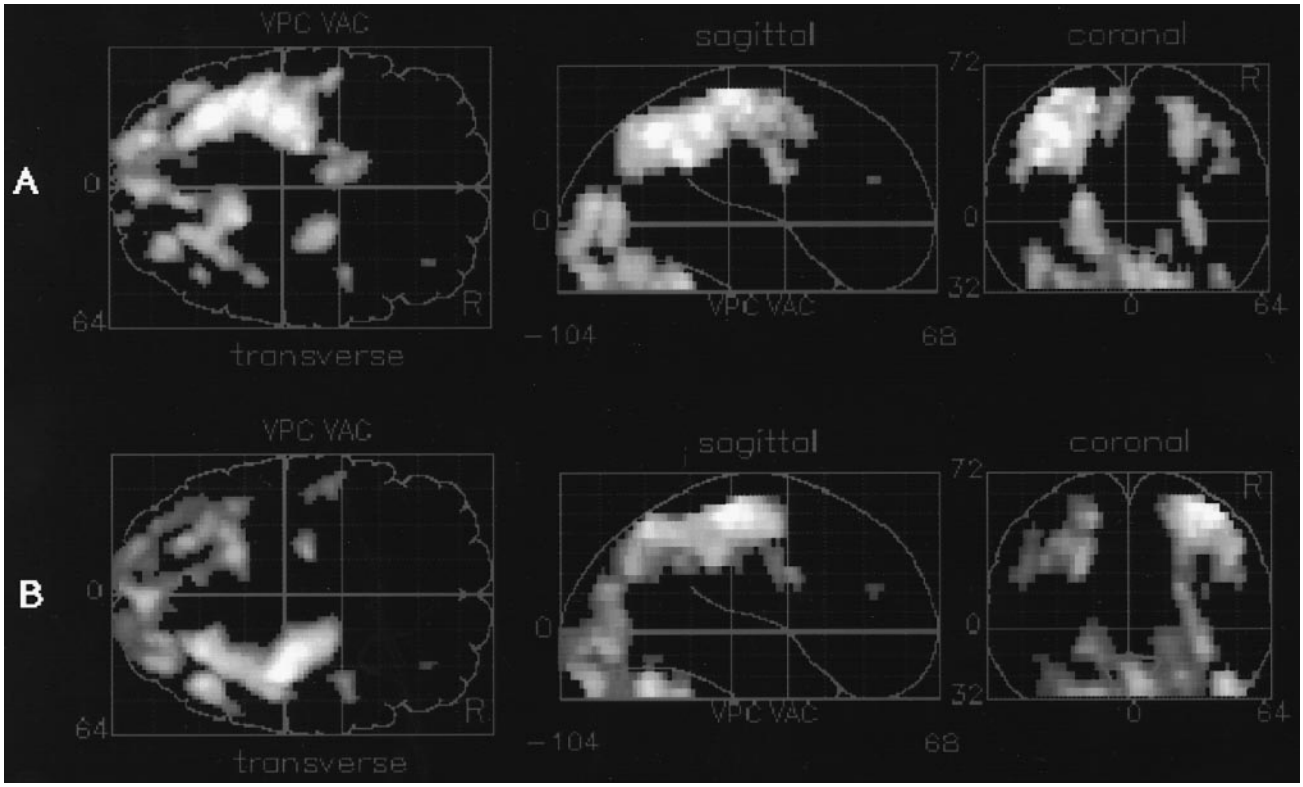

Fig. 1 Comparisons of adjusted mean rCBF between rest and during Braille discrimination task with right (**A**) and left (**B**) index fingers. The results are displayed as statistical maps in three projections with the maximal pixel value displayed along each 'line of sight.' The anterior commissural–posterior commissural (AC–PC) lines are set to zero on the sagittal and coronal projections. Vertical projections of the anterior commissure (VAC) and the posterior commissure (VPC) are depicted on the transverse and sagittal projections. The distances are in millimetres to the left (–) and right (+) of the midline, anterior (+) and posterior (–) to the VAC line, and above (+) and below (–) the AC–PC lines, and correspond to the (x, y, z) coordinates of Talairach and Tournoux (1988). The coloured pixels show levels of statistical significance above $P < 0.05$ with a correction for multiple comparisons.

Non-Braille tactile tasks: sighted subjects (Table 4 and Fig. 4)

The somatosensory control task (sweep condition) in the sighted subjects activated the inferior parietal lobule bilaterally, left primary sensorimotor area, left posterior insula, supplementary motor area, left prefrontal region and the right opercular portion of the precentral gyrus. The activation patterns for each subtask of tactile discrimination (angle, width and character) were similar to the pooled pattern. This pooled pattern compared with the rest condition showed activation in the inferior parietal lobule, superior parietal lobule and primary sensorimotor area bilaterally, left ventral premotor cortex, right prefrontal area, right supramarginal gyrus, left insula, left thalamus, right putamen and left prefrontal region. Each non-Braille discrimination task showed a pattern of deactivation similar to the pooled one. Decreased rCBF was seen in the right medial frontal area, ventral occipital cortex including inferior occipital gyrus, primary visual cortex, precuneus and lingual gyrus, also the anterior temporal region and superior portion of the cerebellum bilaterally, the left prefrontal region and cingulate gyrus. Discrimination tasks, compared with the non-

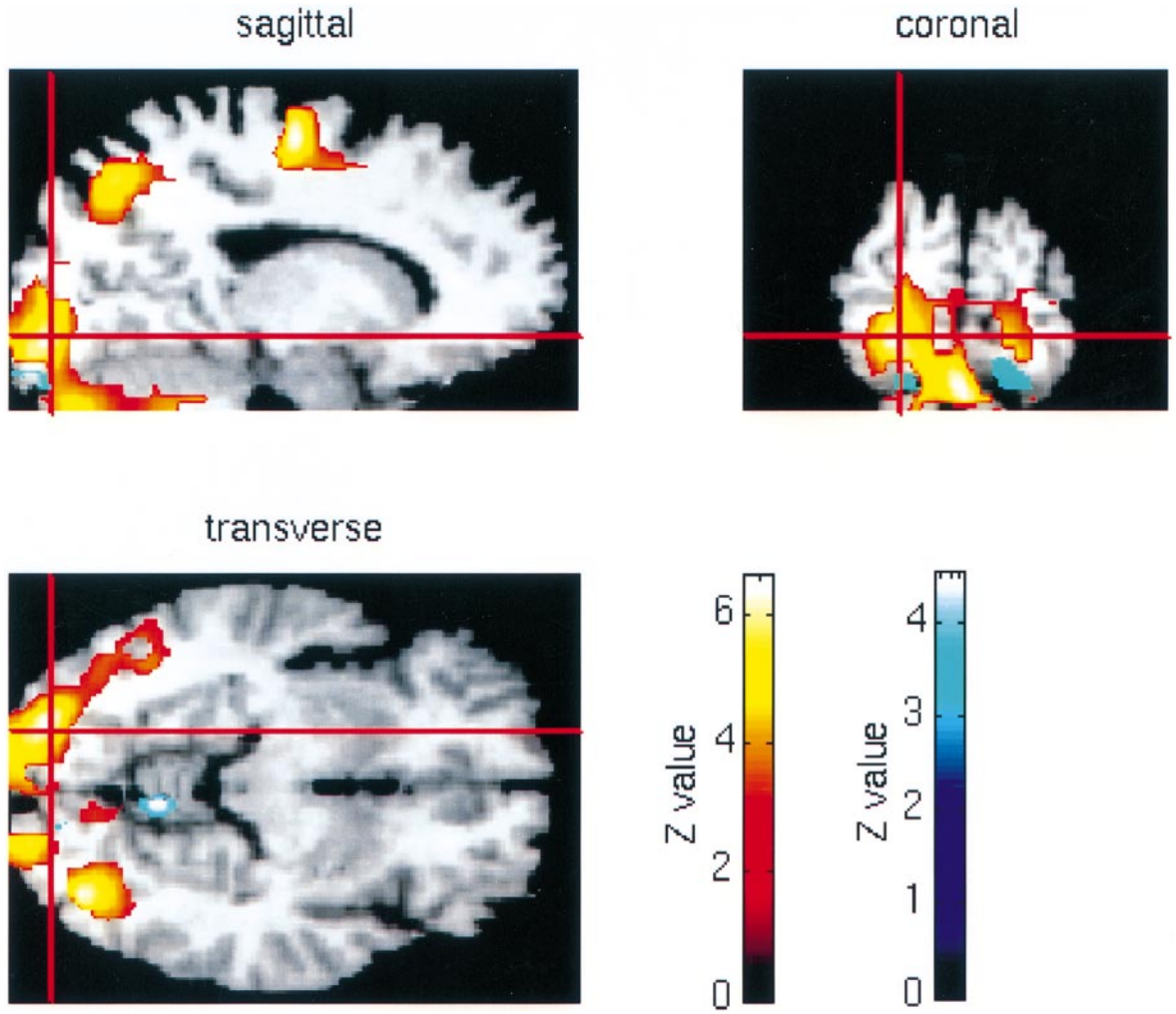

Fig. 2 SPM{*Z*} of conjunction analysis. Consistently activated areas irrespective of the side of the reading finger and onset of blindness are shown (red and yellow). The voxels were commonly activated during Braille reading by earlier onset blind subjects ($n = 4$, onset of complete blindness was 0 year) and later onset groups ($n = 4$, mean onset was 8.5 years) with the index finger of either side, without significant differences among these conditions ($P < 0.05$ with correction for multiple comparisons). Red lines cross at (–18, –94, –8) [$Z = 6.52$, $P < 0.001$ with correction for multiple comparisons], on the left calcarine sulcus. A tendency for more activation by the later onset group than the earlier one is shown in blue ($P < 0.001$, uncorrected).

discrimination task (sweep condition), showed greater activation in the right cerebral hemispheres, including the precuneus, primary sensorimotor area and prefrontal regions (Table 4 and Fig. 4D).

Non-Braille tactile tasks: blind subjects (Table 5 and Fig. 5)

The somatosensory control task (sweep condition) activated the left primary sensorimotor area, left superior parietal lobule and left inferior parietal lobule in the blind subjects. The activation patterns of each subtask of discrimination were similar to the pooled pattern. Each non-Braille discrimination task, when contrasted with the rest condition, showed a pattern similar to the pooled one. The pooled pattern compared with the rest condition showed activation in the inferior parietal lobule, superior parietal lobule, superior occipital gyrus bilaterally, left primary sensorimotor area, right ventral premotor cortex, right prefrontal cortex and left middle temporal gyrus. There was decreased rCBF in the medial prefrontal region, left precuneus, cingulate gyrus, right middle temporal gyrus and left opercular portion of the precentral gyrus.

Blind versus sighted during non-Braille tactile tasks (Table 6 and Fig. 6)

During the sweep condition, there was no significant difference between the blind and the sighted subjects. During the non-Braille tactile discrimination tasks, greater activation in rCBF was noted in the blind than the sighted in the middle occipital gyrus bilaterally, the right fusiform gyrus, right lingual gyrus, right inferior occipital gyrus, left cuneus, left dorsal premotor cortex and left cerebellum. The sighted group

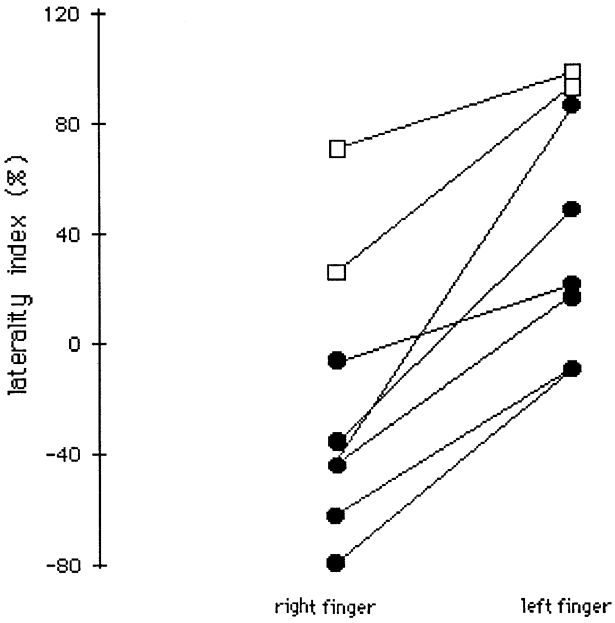

Fig. 3 Laterality index of percentage change in CBF (%ΔCBF) in the primary sensorimotor area. The subjects who prefer using right index finger for Braille reading (closed circles) showed more activation in the left primary sensorimotor area during Braille reading with the right index finger, whereas activation of the right primary sensorimotor area became prominent with the left index finger. In contrast, the subjects who prefer using left index finger for Braille reading (open squares) showed more activation in the right primary sensorimotor area during reading with both right and left index fingers. Laterality index = $(r - l)/(r + l) \times 100$, where r is the %ΔCBF in the right primary sensorimotor area ($x = 28$, $y = -22$, $z = 52$) and l is %ΔCBF in the left primary sensorimotor area (–28, –22, 52). %ΔCBF was calculated with analysis of covariance-adjusted images of task conditions, compared with the rest condition (task – rest).

showed a significant decrease in rCBF in these areas. On the other hand, greater activation was seen in the sighted than the blind in the left postcentral gyrus, left inferior parietal lobule, left opercular portion of the precentral gyrus, right medial portion of the prefrontal region, supplementary motor area, right dorsolateral prefrontal cortex and right supramarginal gyrus. The blind group showed decreased rCBF in these areas, except for the dorsal portion of the left inferior parietal lobule.

Effect of blindness on rCBF during rest (Table 7)

There was no significant difference in rCBF at rest in the primary visual cortex, whereas the association visual cortex of the blind tended to have higher rCBF at rest. The postcentral gyrus [Brodmann area (BA) 43] of the blind, close to the presumed secondary somatosensory area, showed higher rCBF at rest than that of the sighted.

Discussion

Exploratory motor control

Primary sensorimotor area

Braille discrimination tasks in the blind subjects revealed consistent activation in the primary sensorimotor area bilaterally. The sighted subjects also showed activation of the primary sensorimotor area bilaterally during tactile exploratory tasks, whereas only the contralateral primary sensorimotor area was activated during the less complex, 'sweep' condition. The bilaterality appears to be related, partly, to the complexity of the finger movement (Shibasaki *et al*., 1993).

Braille discrimination tasks activated the right primary sensorimotor area more prominently with left index finger reading than reading with the right, whereas the left primary sensorimotor area was activated equally by either the right or left index finger. This pattern is consistent with the postulate that the left hemisphere (in right-handed individuals) is dominant for pre-programmed, open-loop movements (Haaland *et al*., 1987).

The relationship between the preferred finger for Braille reading and activation in the primary sensorimotor area is relevant for plasticity of the sensorimotor system. The primary sensorimotor area contralateral to the preferred finger had a bias for greater activation regardless of which finger was reading. This is probably due to increased excitability of both the primary somatosensory and motor cortices. Non-human primate studies have shown that tactile discrimination training causes the hand representation in cortical area 3 to be reorganized, with an emergence of a large cutaneous representation and parallel disappearance of the representation of deep sensation (Recanzone *et al*., 1992*a*, *b*, *c*, *d*). The authors attributed this to the strengthening of afferent and intrinsic cortical excitatory synapses by behaviourally important, temporally coincident inputs (Recanzone *et al*., 1992*d*). Human studies with blind proficient Braille readers have shown an enlarged sensorimotor representation of the reading finger compared with the homologous finger of their other hand or with either finger in both sighted and blind, non-Braille reading control subjects (Pascual-Leone and Torres, 1993; Pascual-Leone *et al*., 1993). Pascual-Leone *et al*. (1995) also found that motor cortical excitability was rapidly modulated in relation to the amount of preceding Braille reading activity. Hence, elevated rCBF of the primary sensorimotor area contralateral to the preferred hand may be related to increased use over many years in the past, as well as to intense use of the reading finger at present.

Ventral premotor cortex

The premotor cortex plays an important role in generating complex movements (Dum and Strick, 1991). Premotor cortex lesions are characterized by disintegration of skilled movements (Luria, 1966). The premotor cortex in the primate is composed of dorsal and ventral sections which differ

Table 3 *Somatosensory tactile discrimination task with Braille*

Location	Side	Coordinates			Right index finger			Left index finger		
		x	*y*	*z*	*Z*	CBF (%Δ)	*P*-value	*Z*	CBF (%Δ)	*P*-value
Activation by Braille reading with either reading finger										
Inferior parietal lobule (BA 40)	L	−38	−48	32	7.3	11.4	<0.01	5.3	7.3	<0.01
	R	40	−42	40	5.0	8.6	<0.01	6.0	10.7	<0.01
Cuneus (BA 17)	L	−16	−98	−8	5.6	9.7	<0.01	5.2	8.7	<0.01
	R	16	−98	−8	5.0	8.7	<0.01	5.1	8.8	<0.01
Superior occipital gyrus (BA 19)	L	−22	−72	32	5.8	6.7	<0.01	6.2	7.2	<0.01
	R	22	−70	40	6.1	8.8	<0.01	5.8	8.2	<0.01
Ventral premotor cortex (BA 6)	L	−48	−8	28	5.6	6.3	<0.01	5.2	5.8	<0.01
	R	40	2	24	5.3	6.3	<0.01	5.3	6.3	<0.01
Superior parietal lobule (BA 7)	L	−34	−54	44	7.3	11.2	<0.01	4.7	6.2*	0.01
	R	26	−64	48	4.7	5.4	0.01	7.5	10.0*	<0.01
Cerebellum	L	−26	−56	−28	5.6	9.6	<0.01	5.6	9.6	<0.01
	L	−12	−88	−24	5.1	7.6	<0.01	4.8	7.1	<0.01
	L	−40	−70	−28	5.1	7.8	<0.01	4.6	6.8	0.01
	R	24	−62	−24	5.2	8.5	<0.01	5.3	8.5	<0.01
Fusiform gyrus (BA 37)	L	−30	−84	−24	5.5	7.1	<0.01	5.3	6.9	<0.01
	R	42	−64	−24	5.3	6.9	<0.01	7.3	10.7	<0.01
Primary sensorimotor area	L	−18	−18	52	7.0	8.6	<0.01	6.2	7.3	<0.01
	R	28	−22	52	5.1	7.9	<0.01	7.7	14.1*	<0.01
Dorsal premotor cortex (BA 6)	R	22	−8	52	6.2	10.0	<0.01	6.6	11.1	<0.01
Middle occipital gyrus (BA 18)	R	26	−78	4	6.2	10.3	<0.01	5.6	8.8	<0.01
Inferior occipital gyrus (BA 18)	R	30	−82	−4	5.6	9.7	<0.01	5.9	10.2	<0.01
Inferior frontal gyrus (BA 46)	R	34	36	20	4.6	5.5	0.01	4.7	5.6	0.01
Activation by right index finger reading only										
Inferior occipital gyrus (BA 18)	L	−20	−88	8	6.7	8.4	<0.01	4.0	4.6*	0.12
Inferior parietal lobule (BA 40)	L	−36	−38	44	7.6	12.6	<0.01	1.9	2.6*	1.0
Dentate nucleus	R	14	−48	−28	6.7	13.8	<0.01	3.1	5.4*	0.84
Primary sensorimotor area	L	−30	−26	60	7.2	12.1	<0.01	3.6	5.0*	0.36
Supplementary motor area	L	−4	−6	56	5.6	7.6	<0.01	3.9	4.9	0.16
Activation by left index finger reading only										
Dentate nucleus	L	−12	−48	−28	1.3	1.8	1.0	5.6	9.1*	<0.01
Inferior occipital gyrus (B 18)	R	30	−96	−4	1.5	2.8	1.0	4.4	9.3*	0.03

BA = Brodmann area according to Talairach and Tournoux (1988); CBF (%Δ) = percentage change in CBF. *Significant difference in activation during left index finger reading compared with right index finger reading ($P < 0.05$ with correction for multiple comparisons).

anatomically and electrophysiologically (Kurata, 1989; Dum and Strick, 1991; Mushiake *et al*., 1991).

The Braille discrimination task in the blind subjects activated the ventral premotor cortex bilaterally irrespective of reading finger. The ventral premotor cortex is probably equivalent to ventral premotor cortex in primates, because of its ventral location. Non-human primate studies have shown that neurons in inferior area 6 are activated by goal-related motor acts of the hand, dependent upon the way in which the hand was shaped (Rizzolatti *et al*., 1988). Since half of the recorded neurons responded to somatosensory stimuli, these authors speculated that a vocabulary of hand motor acts is formed which can be triggered by somatosensory stimuli. This finding implies that the ventral premotor cortex is important for tactile discrimination tasks. Activation of the ventral premotor cortex bilaterally was also noted during exploratory tactile shape discrimination tasks by the sighted (Seitz *et al*., 1991). Even though the finger movement of the Braille reader is smoother than the sighted, subtle control of the finger movement and its position to keep the contact between fingertip and raised dots, is necessary to maximize the sensitivity of tactile perception. This is probably accomplished by feedback information through the tactile modality. Hence, the ventral premotor cortex may have an important role in tactile–motor integration to control finger movements during tactile discrimination.

Parietal cortex

The inferior and superior parietal lobules were activated during the tactile task by both the blind and the sighted subjects. The inferior parietal lobule is probably related to preparation for movement (Godschalk and Lemon, 1989; Deiber *et al*., 1991). The superior parietal lobule of humans, designated as BA 7, may be homologous to area 7 of macaque monkeys (Haxby *et al*., 1994). Non-human primate studies

Table 4 *Areas activated by non-Braille tactile discrimination task in 10 sighted subjects*

Location	Side	*x*	*y*	*z*	*Z*	%ΔCBF	*P*-value
Sweep–rest							
Inferior parietal lobule	L	−42	−40	48	6.6	9.0	<0.01
	R	52	−34	32	5.0	7.1	<0.01
Primary sensorimotor area	L	−26	−34	56	6.4	8.3	<0.01
Insula	L	−36	−14	4	6.0	6.4	<0.01
Supplementary motor area	R	4	−14	56	5.1	6.9	<0.01
Inferior frontal gyrus (BA 44)	L	−56	2	20	4.3	6.1	0.04
(Opercular) precentral gyrus (BA 6)	R	50	10	8	4.3	4.9	0.04
Discrimination–rest							
Inferior parietal lobule (BA 40)	L	−42	−40	48	10.8	13.6	<0.01
	R	48	−34	32	6.6	7.8	<0.01
	R	38	−54	44	6.4	7.6	<0.01
Superior parietal lobule (BA 7)	L	−36	−56	48	8.9	9.6	<0.01
	R	36	−56	48	5.0	6.2	<0.01
Primary sensorimotor area	L	−28	−24	60	7.6	8.8	<0.01
	R	32	−16	56	7.3	7.6	<0.01
Ventral premotor cortex (BA 6)	L	−56	−2	24	7.2	8.9	<0.01
Inferior frontal gyrus (BA 44)	R	48	2	28	7.5	8.1	<0.01
Middle frontal gyrus (BA 46)	R	32	36	32	6.2	6.4	<0.01
Supramarginal gyrus (BA 39)	R	48	−48	36	6.9	8.0	<0.01
Insula	L	−34	−10	4	5.7	5.4	<0.01
Thalamus	L	−20	−16	4	5.4	7.4	<0.01
Putamen	R	20	16	4	4.6	6.0	0.01
Middle frontal gyrus (BA 9)	L	−34	26	32	4.4	4.1	0.03
Rest–discrimination (decrease in rCBF with discrimination)							
Superior frontal gyrus (BA 8)	L	−18	16	56	−7.4	−7.9	<0.01
(Medial) superior frontal gyrus (BA 10)	L	−12	52	4	−6.9	−8.0	<0.01
Superior frontal gyrus (BA 10)	L	−22	56	12	−6.6	−7.2	<0.01
Inferior occipital gyrus (BA 18)	R	30	−84	−12	−7.0	−10.2	<0.01
	R	44	−70	0	−4.7	−5.5	0.01
Cuneus (BA 17)	L	−24	−94	0	−6.9	−9.4	<0.01
	L	−8	−98	−12	−5.1	−5.6	<0.01
Lingual gyrus (BA 18)	R	18	−70	−8	−6.9	−8.5	<0.01
Precuneus (BA 7)	L	−6	−44	56	−4.3	−4.6	0.04
	R	16	−46	52	−5.1	−6.1	0.04
Cingulate gyrus		0	16	−8	−4.7	−6.6	0.01
Inferior frontal gyrus (BA 45)	L	−46	32	4	−4.5	−5.0	0.02
Discrimination–sweep							
Precuneus (BA 7)	R	24	−72	44	6.3	6.9	<0.01
Primary sensorimotor area	R	30	−16	56	5.5	5.6	<0.01
Middle frontal gyrus (BA 10)	R	30	50	12	5.3	6.0	<0.01
Middle frontal gyrus (BA 46)	R	30	38	28	4.3	3.7	0.04
Inferior frontal gyrus (BA 44)	R	44	6	28	5.1	4.9	<0.01
Superior occipital gyrus (BA 19)	R	28	−82	24	4.4	5.2	0.03
Precuneus (BA 7)	L	−22	−78	44	4.9	5.8	<0.01
Inferior parietal lobule (BA 40)	L	−38	−38	48	4.7	5.0	<0.01
	L	−36	−62	44	4.4	4.2	0.03
	L	−40	−50	48	4.2	4.7	0.05

BA = Brodmann area according to Talairach and Tournoux (1988); %ΔCBF = percentage change in CBF.

have suggested that BA 7 is involved in multimodal integration of external information, providing a sensory representation of extrapersonal space (Leinonen *et al*., 1979; Savaki *et al*., 1993). Human PET studies have shown that BA 7 is related to motor selection with sensory cues (Seitz *et al*., 1990; Deiber *et al*., 1991; Grafton *et al*., 1992*a*, *b*). In our study, the superior parietal lobule contralateral to the reading finger was more activated than the ipsilateral superior parietal lobule, suggesting that the superior parietal lobule is involved in the movement selection of the contralateral finger.

Right hemisphere dominance

In blind subjects, both hemispheres were equally included during the Braille reading task irrespective of the side of the reading finger (Table 3). Sighted subjects showed multiple

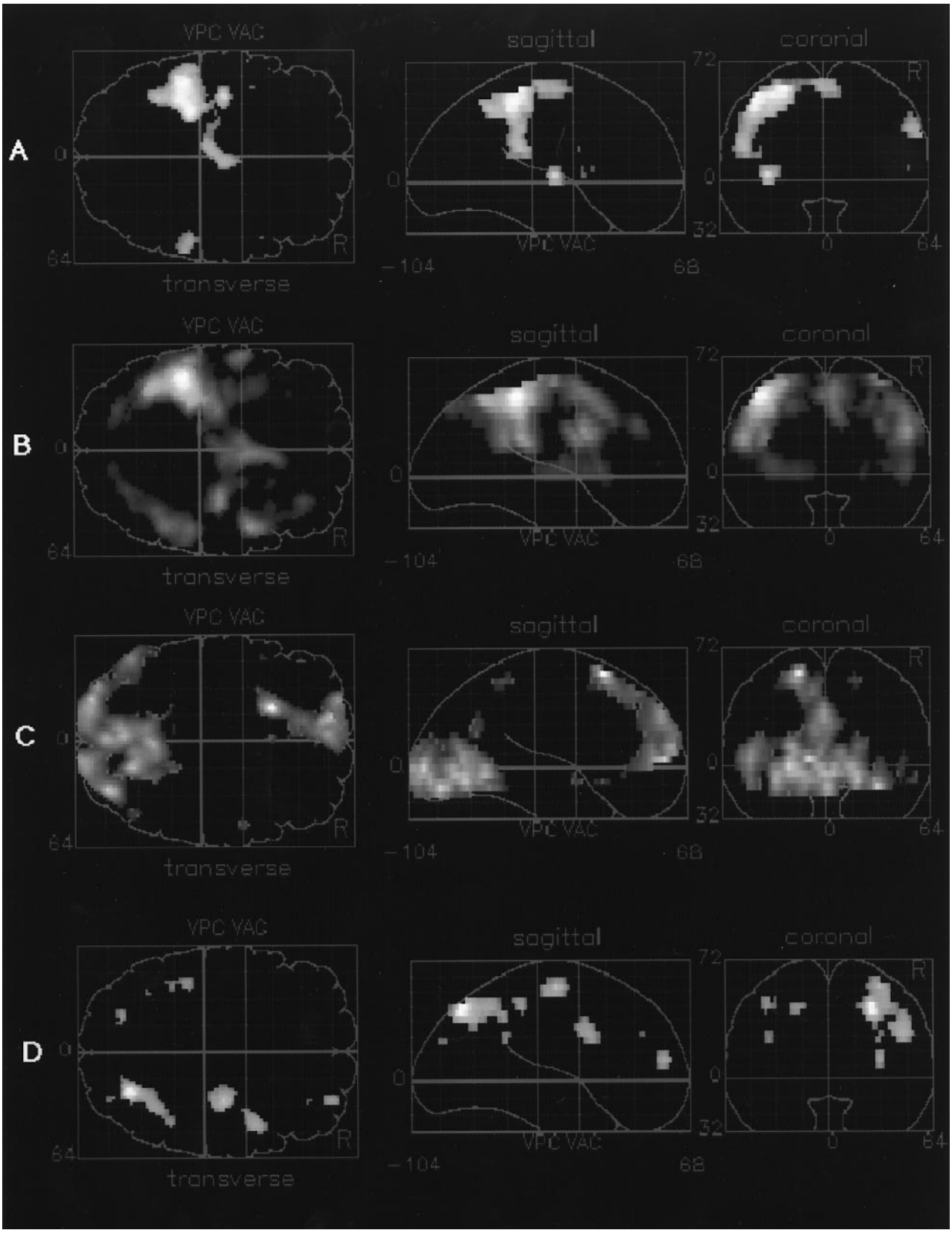

Fig. 4 Comparisons of adjusted mean rCBF during tactile tasks with that at rest, in the sighted subjects: increases in rCBF during (**A**) the non-discriminatory control task (sweep condition) and (**B**) the tactile non-Braille discrimination task, and the decreases in rCBF during the tactile non-Braille discrimination task (**C**). (**D**) Increase in rCBF during discrimination task compared with sweep condition. The pixels show levels of statistical significance above $P < 0.05$ with a correction for multiple comparisons.

Table 5 *Areas activated by non-Braille tactile discrimination task in six blind subjects*

Location	Side	*x*	*y*	*z*	*Z*	%ΔCBF	*P*-value
Sweep–rest							
Primary sensorimotor area	L	−26	−14	44	5.4	12.5	<0.01
Superior parietal lobule (BA 7)	L	−28	−60	48	5.4	8.3	<0.01
Inferior parietal lobule (BA 40)	L	−38	−38	36	5.2	10.3	<0.01
Discrimination–rest							
Inferior parietal lobule (BA 40)	L	−38	−40	36	7.0	12.1	<0.01
	R	32	−48	32	5.8	10.4	<0.01
Superior parietal lobule (BA 7)	L	−28	−60	48	6.0	8.3	<0.01
	R	28	−60	48	4.7	6.7	0.01
Superior occipital gyrus (BA 19)	L	−28	−64	44	7.0	9.5	<0.01
	R	24	−70	40	6.4	8.7	<0.01
Primary sensorimotor area	L	−32	−14	48	6.1	10.1	<0.01
Premotor cortex (BA 6)	R	34	−8	48	5.0	6.3	<0.01
Inferior frontal gyrus (BA 44)	R	44	2	24	4.8	5.9	0.01
Middle temporal gyrus (BA 22)	L	−42	−36	4	4.5	6.7	0.02
Rest–discrimination (decrease in rCBF with discrimination)							
(Medial) superior frontal gyrus (BA 10)	R	10	50	12	−6.5	−8.6	<0.01
Precuneus (BA 7)	L	−6	−38	44	−5.2	−6.1	<0.01
Cingulate gyrus (BA 32)		0	18	−8	−4.8	−8.5	0.01
Middle temporal gyrus (BA 21)	R	56	−4	−4	−5.0	−8.8	<0.01
(Opercular) precentral gyrus (BA 6)	L	−48	−10	12	−4.9	−6.1	<0.01

BA = Brodmann area according to Talairach and Tournoux (1988); %ΔCBF = percentage change in CBF.

cortical regions in the right cerebral hemisphere activated during the discrimination task using the right index finger. Also, their right hemisphere was more activated during the tactile discrimination task than during the non-discrimination sweep condition. These findings are consistent with the notion that tactual perception of pattern and shape involves the right hemisphere more than the left (Carmon and Benton, 1969; Fontenot and Benton, 1971; Zaidel and Sperry, 1973). Such dominance may be related to the fact that left-handed Braille letter reading by the blind is more accurate than the right (Hermelin and O'Connnor, 1971).

Blind subjects showed activation of the right dorsal premotor cortex and the right prefrontal cortex during tactile discrimination tasks, irrespective of the finger used for reading. The human PET study of Gitelman *et al*. (1996) has shown that exploratory tasks with the right hand activate the right premotor and posterior parietal areas; they attributed this to the exploratory motor aspects of spatial attention. Because the right dorsal premotor cortex and right prefrontal cortex are related to visuospatial working memory (Jonides *et al*., 1993), they are components of a functional network for modality-independent extrapersonal spatial attention which may be required for exploratory finger movement.

Cerebellum

During the Braille discrimination task by the blind, the lateral portions of the cerebellar hemispheres were activated bilaterally, irrespective of reading finger, and the dentate nucleus was activated ipsilaterally. To guide voluntary movement, signals from the prefrontal and posterior parietal cortex (area 7) pass not only directly to the motor cortex, but also via the pontine nuclei to the lateral cerebellar cortex, thence via the dentate nucleus to the thalamus, and finally to the motor cortex (Stein, 1986). Tactile discrimination tasks necessitate greater processing of somatosensory feedback than simple finger movement; hence, increased activation of area 7 and the lateral cerebellar hemispheres is reasonable. Activation of the ipsilateral dentate nucleus is probably related to the cerebellar output to the contralateral motor cortex. A similar activation pattern was shown by tactile shape discrimination by the sighted (Seitz *et al*., 1991), suggesting a role for the cerebellum in exploratory motor control.

The cerebellar activation noted in the present study might also be related to the cognitive processes of tactile and/or lexical discrimination (Leiner *et al*., 1993; Petersen and Fiez, 1993; Kim *et al*., 1994; Raichle *et al*., 1994; Andreasen *et al*., 1995; Gao *et al*., 1996), since our task design could not separate the sensorimotor component of Braille reading from a lexical or cognitive process.

Transfer of sensory information for tactile discrimination

The blind subjects showed suppression of the parietal operculum and activation of the ventral portion of the occipital cortex during tactile discrimination tasks, opposite to the pattern of the sighted.

Since we did not try to control the subjects' thought during the rest condition, 'activation' at rest by visual or tactile

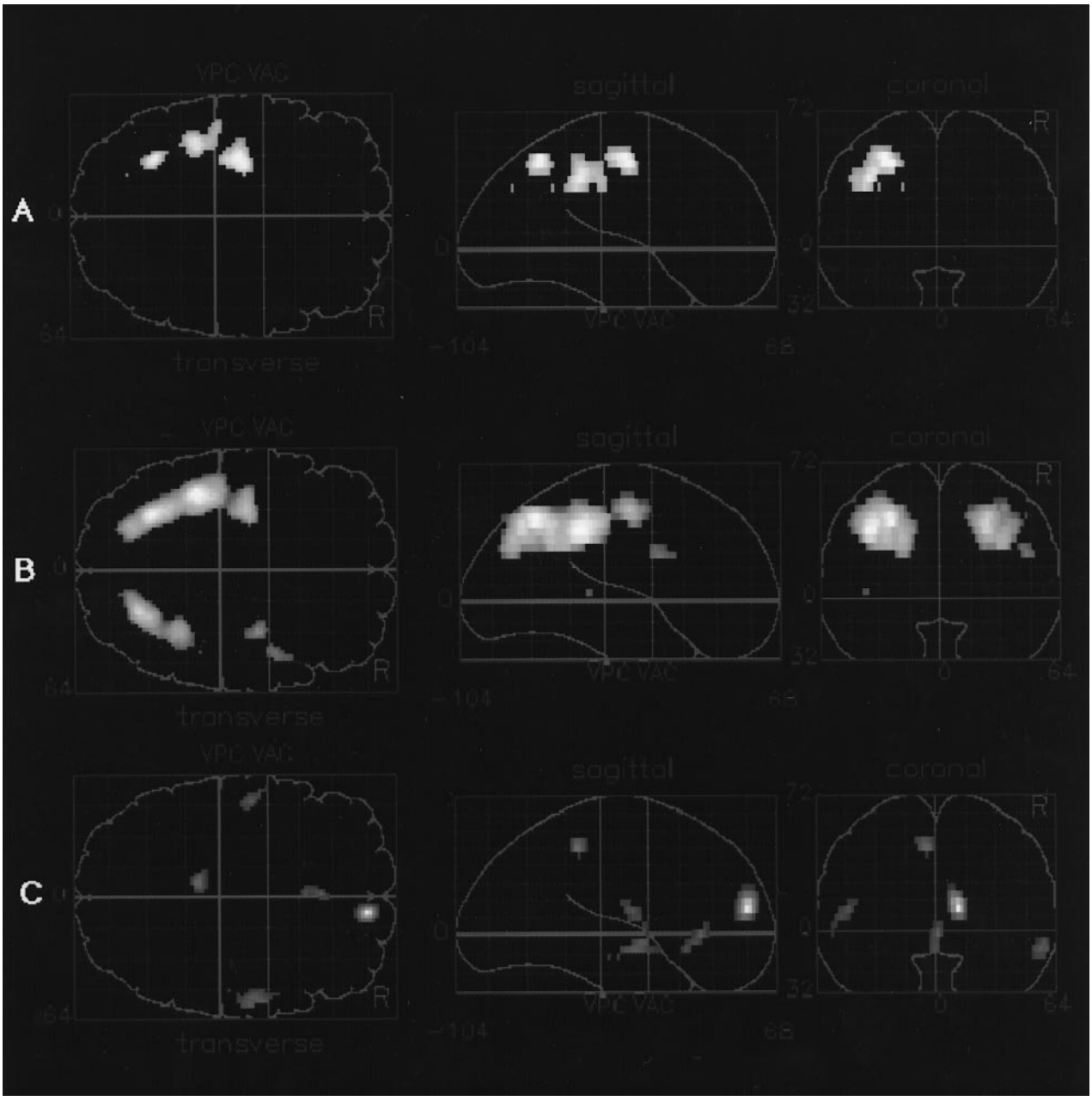

Fig. 5 Comparisons of adjusted mean rCBF during tactile tasks and at rest in the blind subjects: increases in rCBF during (**A**) the non-discriminatory control task (sweep condition) and (**B**) the tactile non-Braille discrimination task, and decreases in rCBF during the tactile non-Braille discrimination task (**C**). The pixels show levels of statistical significance above $P < 0.05$ with a correction for multiple comparisons.

imagery might be a cause of different behaviour between the sighted and blind. However, because both visual and tactile cortices of the blind showed higher rCBF than those of the sighted, different activation patterns between the sighted and blind subjects during tactile discrimination tasks is unlikely to be explained by 'activation' at rest.

Whereas two-group analysis showed relative activation of areas 17 and 18 of the blind subjects during non-Braille tactile discrimination, compared with the sighted group, activation of areas 17 and 18 during non-Braille tactile discrimination by the blind subjects did not reach statistical significance by single-study analysis. This is probably because the task load was relatively small for proficient Braille readers; hence, a smaller activation could be expected. However, the two-group analysis showed that the behaviour of the visual cortex of the blind was opposite to that of the sighted subjects during tactile discrimination tasks. With the context of the activation of these areas during Braille reading, the visual cortex of the blind may play a role in non-Braille tactile discrimination tasks.

Deactivation of the visual cortex of the sighted and of the parietal operculum of the blind is unlikely to be due to

Table 6 *Comparison between the blind and sighted groups in %ΔCBF during the non-Braille tactile discrimination task compared with rest*

Location	Side	*x*	*y*	*z*	*Z*	*P*	Blind (n = 6) %ΔCBF (*Z*)	Sighted (n = 10) %ΔCBF (*Z*)
Greater activation in the blind than the sighted								
Middle occipital gyrus (BA 19)	L	−48	−72	−8	6.3	<0.01	5.6 (3.8)	−6.4 (−5.6)
Fusiform gyrus (BA 19)	R	18	−68	−8	5.9	<0.01	3.2 (2.1)	−8.5 (−6.8)
Lingual gyrus (BA 19)	R	16	−74	0	5.8	<0.01	5.0 (3.1)	−7.3 (−5.6)
Inferior occipital gyrus (BA 18)	R	30	−86	−8	5.4	<0.01	3.3 (2.0)	−8.9 (−6.3)
Cuneus (BA 17)	L	−6	−100	−12	5.6	<0.01	4.6 (3.4)	−5.4 (−5.0)
Premotor cortex (BA 6)	L	−18	14	56	5.1	<0.01	0.7 (0.6)	−7.6 (−7.2)
Cerebellum	L	−4	−64	−8	5.1	<0.01	3.0 (1.8)	−8.0 (−5.9)
Greater activation in the sighted than the blind								
Postcentral gyrus (BA 40)	L	−50	−28	16	5.9	<0.01	−3.4 (-2.8)	6.2 (6.2)
Postcentral gyrus (BA 5)	L	−22	−34	56	5.1	<0.01	−1.6 (-1.2)	7.2 (6.6)
Inferior parietal lobule (BA 40)	L	−50	−38	24	5.8	<0.01	−1.7 (-1.4)	7.5 (7.4)
(Opercular) precentral gyrus	L	−38	−10	12	5.5	<0.01	−3.7 (-3.1)	5.2 (5.3)
(Medial) superior frontal gyrus (BA 10)	R	12	48	12	5.3	<0.01	−8.0 (-5.8)	1.3 (1.2)
Supplementary motor area	L	−2	−20	60	4.9	<0.01	−2.7 (-2.2)	5.4 (5.3)
Inferior frontal gyrus (BA 45)	R	52	16	4	4.5	0.02	−4.3 (-2.3)	6.8 (4.5)
Supramarginal gyrus (BA 39)	R	48	−44	28	4.4	0.03	−1.3 (-1.0)	6.3 (5.7)

BA = Brodmann area according to Talairach and Tournoux (1988); %ΔCBF = percentage change in CBF.

an artefact of global normalization because of the spatial discreteness (Grabowski *et al*., 1996). Instead, it might have been caused by a shift of attention. During rest condition, sighted subjects might have undergone visual imagery. Once the task of the other modality starts, their attention might shift toward it; thus, activity of the visual cortex decreases. This kind of cross-modal suppression has been reported previously (Haxby *et al*., 1994; Kawashima *et al*., 1995). It is important that attentional shift also causes the activation of the cerebral regions representing the modality to which the attention was shifted (Meyer *et al*., 1991). It is reasonable to speculate that the same cross-modal suppression might have occurred in the blind subjects. During tactile discrimination, attentional shift to the modalities in use may occur. Considering the changed function of the visual cortex in the blind, suggested by the previous transcranial magnetic stimulation study (Cohen *et al*., 1997), attentional shift might augment the activation of the visual cortex which is in use and suppress the parietal operculum which is not in use. These findings suggest a modification of the pathway for tactile discrimination in the blind.

The secondary somatosensory area in humans has been localized to the parietal operculum within the sylvian fissure (Burton *et al*., 1993). The non-human primate ablation study of Murray and Mishkin (1984) showed that the secondary somatosensory area is a critical station in a tactile processing pathway from the primary somatosensory cortex to the limbic structures. In humans, the present and previous PET studies confirmed activation of the secondary somatosensory area during tactile discrimination tasks by sighted subjects (Burton *et al*., 1993; Ledberg *et al*., 1995).

A sequential striate–prestriate–inferior temporal cortical pathway (ventral visual pathway) is known to serve visual discrimination (Ungerleider and Mishkin, 1982). In macaque monkeys, ablation of the posterior part of the inferior temporal cortex (area TEO) leads to severe visual pattern discrimination deficits (Blake *et al*., 1977). Area TEO in macaques may correspond to BA 37 (Damasio and Damasio, 1989; Desimone and Ungerleider, 1989). Recent PET studies with humans suggest that the fusiform gyrus, BA 37, is related to visual shape discrimination (Petersen *et al*., 1988, 1990; Corbetta *et al*., 1990; Haxby *et al*., 1991, 1994; Sergent *et al*., 1992; Buckner *et al*., 1995)

Murray and Mishkin (1984) suggested an analogy between pathways concerned with visual and tactile shape discrimination. They indicated that, in macaque monkeys, the secondary somatosensory area for touch discrimination may be analogous to area TEO for visual pattern discrimination.

During Braille reading, the dorsolateral occipital cortices of the blind subjects were activated bilaterally. The PET study of Roland *et al*. (1989) with sighted subjects showed that a tactile discrimination task activated the parietal cortices, but not the occipital cortex. In the monkey, the posterior parietal cortex (area 7) is interconnected with the visual association cortex (dorsolateral area 19) (Bruce *et al*., 1981). Early visual deprivation in the monkey made most neurons in area 7 and 19 responsive to somatic exploration (Hyvarinen *et al*., 1981). Diffuse reciprocal projections link area 19 to the primary visual cortex (Shipp and Zeki, 1989). Hence, somatosensory input could be transferred to the primary visual cortex through the dorsal visual association areas (Sadato *et al*., 1996).

Taking these findings together, the spatial information originally conveyed by the tactile pathway in the sighted subjects (from the primary to the secondary somatosensory area) might, in the blind, be processed by the neuronal

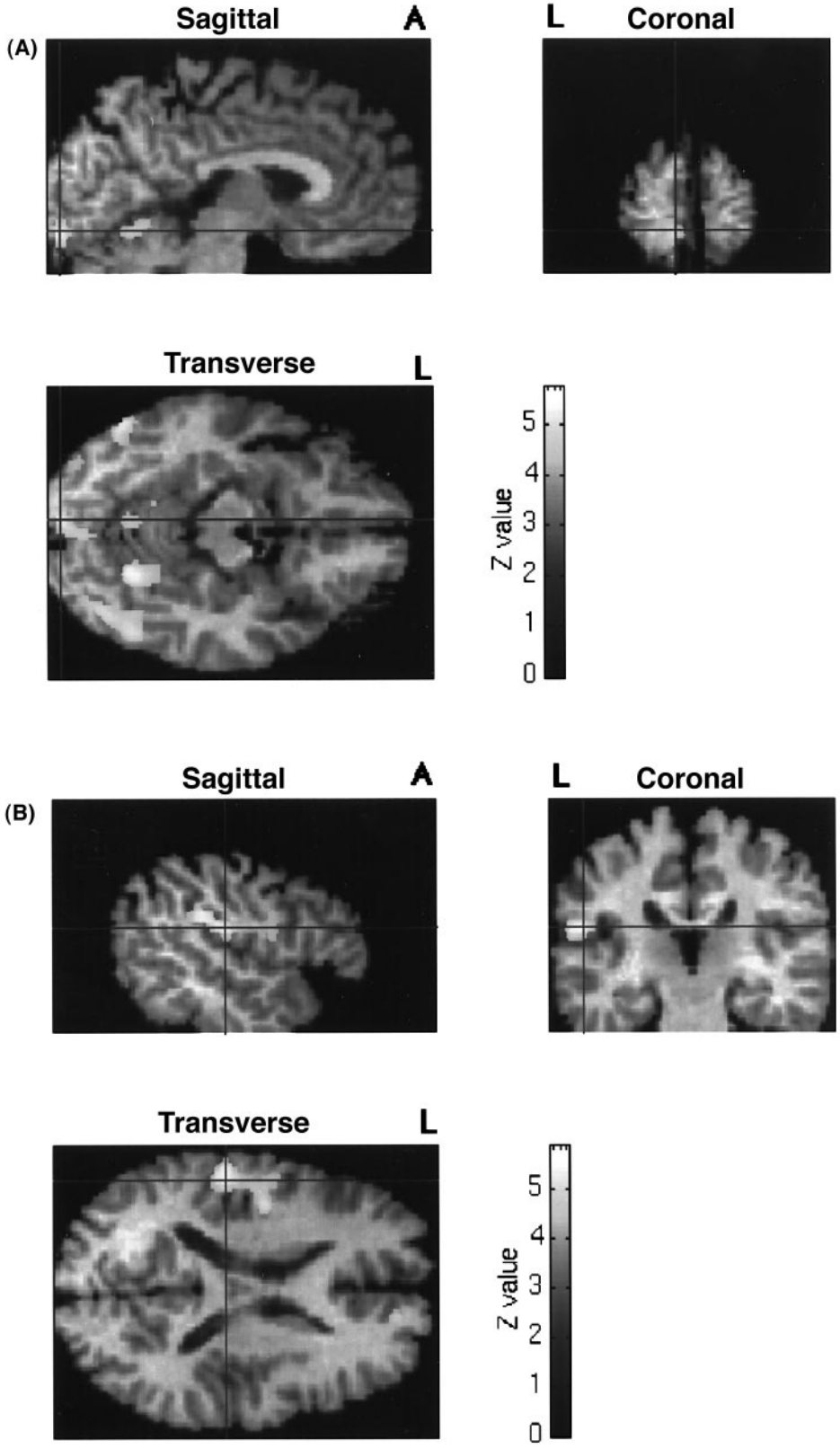

Fig. 6 Comparisons, between the sighted and the blind subjects, of differences in rCBF during non-Braille tactile discrimination task and the rest condition: (**A**) areas of greater activation in the blind than the sighted and (**B**) areas of greater activation in the sighted than the blind. A statistical parametric map of between-group comparisons in three orthogonal sections was superimposed on a typical anatomical MRI, unrelated to the study subjects. The black lines indicate the projections of each section that cross the centre of the primary visual cortex (–6, –100, –12) in **A**, and the left parietal operculum (–50, –28, 16) in **B**. The pixels show levels of statistical significance above $P < 0.05$ with a correction for multiple comparisons.

Table 7 *Effect of blindness on rCBF at rest*

Location	Side	*x*	*y*	*z*	*Z*	Corrected *P*
Blind>sighted						
Inferior occipital gyrus (BA 19)	R	42	−74	12	5.2	<0.01
Inferior occipital gyrus (BA 19)	R	30	−88	−12	4.6	0.01
Insula	L	−28	−10	12	4.9	0.01
Superior frontal gyrus (BA 10)	L	−22	44	24	4.7	0.01
Parahippocampal gyrus	L	−26	−30	−4	4.7	0.01
Postcentral gyrus (BA 43)	L	−42	−18	16	4.6	0.01
Thalamus	R	22	−20	8	4.4	0.03
Precuneus (BA 18)	L	−14	−70	28	4.4	0.04
Sighted>blind						
Superior temporal gyrus (BA 22)	L	−62	−36	12	5.1	<0.01
Middle temporal gyrus (BA 21)	L	−52	2	−12	4.4	0.04

networks usually reserved for the visual shape discrimination process (from the primary somatosensory area to BA 7, dorsolateral BA 19, V1 and occipitotemporal regions). There is psychological evidence that spatial coding depends on the integration and organization of multimodal inputs (Millar, 1994). Both touch and visual systems code for shape. The convergence of complementary inputs are important in coding and organizing apparently disparate inputs (Millar, 1994). Absence of vision biases inputs for shape information toward touch. Thus, it is reasonable that the visual cortex was freed for processing tactile information in the blind.

Activation of the visual cortices appears to be related to abstract information (in our case, the shape information) rather than the modality of sensory input. In order for a behavioural reaction to a particular stimulus to be appropriate, it is necessary that the same code is used regardless of sensory modality (Rauschecker, 1995). Our results suggest that amodal spatial codes originally conveyed by the somatosensory modality project to the ventral visual pathways in early blind subjects. Although our study could not strictly control the onset of the blindness, all blind subjects had lost their sight before learning to read by sight. Four subjects, blind from birth, never had any light exposure. Two of the later onset blind subjects suffered from retinolental fibroplasia caused by neonatal oxygen intoxication and had had no experience of 'normal vision' even though they did have some light perception. The other two subjects had normal vision for several years before their blindness occurred. Irrespective of the difference of their history of light exposure, the primary visual cortex was commonly activated. The tendency for more extensive areas of activation in later onset blind subjects than early onset ones did not reach statistical significance. Therefore, our data suggest that the history of light exposure is not essential for, nor does it prevent, activation of the visual cortex during Braille reading, at least in the early onset blind patients. Because all our subjects were early onset blind, further study with larger numbers of subjects with a broader range of ages of onset is necessary to determine whether the pattern depends on the time of onset of blindness. Finally, assessment of the neural representation of the linguistic component of Braille reading is also open to question.

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