## RESEARCH ARTICLE

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# An event-related fMRI study of self-paced alphabetically ordered writing of single letters

**Abstract** The spatial location of activation for writing individual letters and for writing simple dots was studied using event-related functional MRI. Ten healthy right-handed subjects were scanned while performing two different protocols with self-paced repetitive movement. In the first protocol with self-paced dot writing, we observed significant activation in regions known to participate in motor control: contralateral to the movement in the primary sensorimotor and supramarginal cortices, the supplementary motor area (SMA) with the underlying cingulate, in the thalamus and, to a lesser extent, in the ipsilateral inferior parietal and occipital cortices. In the second protocol, we investigated an elemental writing feature—writing single letters. We observed statistically significant changes in the premotor, sensorimotor and supramarginal cortices, the SMA and the thalamus with left predominance, and in the bilateral premotor and inferior/superior parietal cortices. The parietal region that was active during the writing of single letters spanned the border between the parietal superior and inferior lobuli Brodmann area (BA 2, 40), deep in the intraparietal sulcus, with a surprising right-sided dominance. The direct comparison of the results of the two protocols was not significant with a confidence level of $P < 0.05$ corrected for whole brain volume. Thus, the ROI approach was used, and we tried to find significant differences within the two predefined regions of interest (ROI) (BA 7, BA 37). The differences were found with a confidence level of $P < 0.05$ corrected for the volume of these predicted areas. The ROI were located in the posterior parts of hemispheres, in the ventral and in the dorsal visual pathway. The right-sided posterior cortices may play a role in the elemental mechanisms of writing. It is possible that activation of this region is linked with the spatial dimension of the writing.

**Keywords** Self-paced · Writing · Functional MRI · Letters · Bereitschaftspotential

## Introduction

The functional neuroanatomy of writing has not yet been fully understood despite the fact that it has been investigated since the 19th century. Various aspects of writing can be impaired by damage to certain brain regions, such as the Broca and Wernicke speech areas, the superior frontal gyrus (Exner's writing area), the supramarginal and angular gyrus, and the superior parietal lobe with adjacent parts of the inferior parietal lobule. Agraphia can be an isolated disorder, but usually it is one of the features of a complex brain function disturbance. For example, it may be a feature of Gerstmann's syndrome when it is localized to circumscribed damage in the angular gyrus. Writing is a very complex activity, involving various cognitive functions, including attention and working and long-term memory. Writing additionally has phonological and semantic aspects, involving sensory feedback and visuospatial, motor, and ideomotor features. It is not surprising that the anatomical distribution of the brain network that is active with writing is complex. Writing requires complex analysis, and the ability to distinguish between the various aspects of these complex phenomena is rather difficult. Therefore, we decided to investigate an elemental feature of writing: the writing of single letters. Our interest was focused on the elemental programming of writing. The cognitive load of this task is relatively low: the writing of letters in alphabetical order is an overlearned, near-automatised activity. There have been few investigations of writing in healthy subjects. In these investigations, writing has mostly been cued by some

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external input, such as reading or dictation. In order to simplify the protocol for our study, we excluded visual feedback and external cues. External cues are a factor that further increases the complexity of writing tasks and makes analysis even more difficult. Thus, in our study, the writing was self-initiated. We chose a self-paced protocol because we have already performed a series of studies with intracerebral recordings of brain electrical activity related to simple and complex self-paced movements, and our knowledge of the map of electrically active brain areas in this kind of protocol is quite reliable (Rektor et al. 1994, 1998, 2001a, b, c; Rektor 2003).

In order to simplify the analysis of this very complex activity, we have chosen to analyse the simplest element—the writing of single letters. In order to separate the writing from other aspects of the protocol, i.e. from cognitive-motor preparation of a movement, we compared the self-paced writing of single letters with the self-paced writing of dots. The aim of this study was to localise the brain regions specific for writing.

## Materials and methods

### Subjects

Ten volunteers participated in our study, all right-handed healthy subjects (two females and eight males) from the professional or academic sector, none of whom had a history of neurological or psychiatric disease. The mean age was $23.5 \pm 1.28$ (SD) years, ranged from 20 to 25 years. Czech was the primary language of all subjects. Informed consent was obtained from each subject after all of the procedures had been fully explained, and the study received the approval of the local ethics committee.

### Task

Subjects were instructed to fix their gaze on the line at the top of the MR gantry, and to keep their eyes open. Since the subject was supine in the scanner, he could not see what he was writing. The task had two parts, each with a duration of 6 min. Both parts were measured together, with a 12 min overall duration of the functional acquisitions. Subjects were instructed to switch from the first part of the task to the second part in response to a speech command from the computer. In the first part, subjects were instructed to write dots. They were asked to write the dots slowly, holding the pen on the tablet for a while. This was done in order to minimize the difference between the two protocols, as the writing of letters was expected to take a longer time than the writing of dots.

In the second part, subjects were instructed to write the letters of the alphabet (beginning with the letter "a") without diacritics. The start of the trial (either writing dots or single letters) was determined by the subject. Subjects were instructed not to perform the requested event more than once in 20 s, to write the letters slowly without breaking the contact of the special opto-mechanical pen on the tablet, and to minimize hand movements in the rest periods. The requested movement was supposed to be started after an estimated interval of approximately 20 s without overt counting of seconds. The subjects were asked to estimate the approximate interval covertly, without any external or internal cue. The time interval estimation and the writing tasks were practised prior to the functional MRI (fMRI) examination.

The tablet was held in the subject's left hand, and the pen was held in the subject's right hand. The tablet was rested freely on the subject's abdomen. The opto-mechanical pen was equipped with a touch scanner, and was connected to the computer via fibre optic cable. The computer recorded information about the initialisation and completion of contact between the pen and the pad. While writing the letters, any break in contact was interpreted as a mistake, and the event was eliminated from further analysis. An interview was performed with each subject after the examination to evaluate the subject's assessment of the task qualities. The mean time (across all subjects) of writing a dot was $3.50 \pm 2.78$ s; of writing a letter, it was $5.49 \pm 1.61$ s. The mean periods between trials were: for dots, $28.7 \pm 9.6$ s; for letters, $28.9 \pm 7.4$ s. The mean number of successful trials were $11.4 \pm 3.9$ for dots, and $11.2 \pm 3.4$ for letters.

### MR acquisition

Imaging was performed on a 1.5 T Siemens Magnetom Symphony scanner. Gradient echoplanar (EPI) imaging was used for functional images: TR (scan repeat time) = 2,760 ms (including 1 s of silence), TE = 40 ms, flip angle = 90°, FOV = 230 mm, slice thickness = 5 mm, inter-slice gap = 2 mm, 16 transversal slices, inplane resolution 64×64. A total of 260 functional scans were acquired from each subject for an overall study (130 scans for dots and 130 scans for letters). Following functional measurements, high-resolution T1-weighted anatomical images were collected using a 3D sequence with the following parameters: 160 sagittal slices, inplane resolution 512×512, slice thickness = 1.17 mm, TR = 1,700 ms, TE = 3.96 ms, FOV = 246 mm, flip angle 15°.

### Funtional MRI data analysis

Functional MRI data were analysed using the SPM99 (Wellcome Department of Cognitive Neurology, London, UK) program, using a statistical parametric mapping and general linear model. The starting point of events aligned for analysis was the first contact of opto-mechanical pen with the tablet. Several scans from each

functional series (as many as needed for excluding the first event in both kind of tasks) were excluded from the analysis. Functional scans were realigned (motion correction), normalised to the MNI template, and smoothed (using a Gaussian filter with a full width at half maximum of 6 mm). Functional series were filtered with a high-pass filter (cut-off period of 90 s) and a low-pass filter (Gaussian kernel with a full width at half maximum of 4 s). Both the times at which the subject started writing and the duration of the writing process were used to establish the experimental time series. The canonical hrf and its temporal and dispersion derivatives were used as basis functions or regressors of interest for both task types (dots and letters), and movement parameters were used as regressors for excluding movement-related effects. Statistical parametric maps (SPM) (F) (time and dispersion derivatives were incorporated into the final $F$ contrast) resulting from the individual task types, and linear contrasts between the task types, were computed and then used for single-subject (first-level) inferences with a $P < 0.05$ threshold, corrected for multiple comparisons. The $t$-contrast files were generated individually for each regressor (dot-canonical hrf, dot-temporal derivative, dot-dispersion derivative, letter-canonical hrf, letter-temporal derivative and letter-dispersion derivative) or contrasts of regressors, for use in second-level analysis. This random effect analysis was made using ANCOVA with the three regressors of interest (canonical hrf, its temporal derivatives and its dispersion derivatives) and mean trial duration per subject as a covariate for reduction of its impact on group analysis. SPM (F) were calculated using $F$ contrast. We used a statistical threshold of $P < 0.05$ corrected for multiple comparisons. While evaluating differences between the writing of letters and dots, significant activations were not observed at a threshold of $P < 0.05$ corrected for whole brain volume. We used a regions of interest (ROI) analysis, as implemented in SPM99 using the small volume correction (SVC) option. Two specific regions, the ventral extrastriate cortex, including BA 37 (Roland and Gulyás 1994; Petrides et al. 1995; Nakamura et al. 2000; Flowers et al. 2004) and the superior parietal lobule (SPL), including BA 7 (Stephan et al. 1995; Matsuo et al. 2000; Menon and Desmond 2001), were verified, and corrected $P$ values were calculated. Subsequently, the resulting figures of these activations (differences between the two tasks) were carried out using masked contrast files entering into the second-level analysis and corrected threshold of $P < 0.05$. This gives us pictures of activations with the same corrected statistical values as using SVC.

## Results

In the second protocol, we investigated an elemental writing feature—writing single letters. We observed statistically significant changes in the premotor, sensorimotor and supramarginal cortices and thalamus with left predominance, and in the bilateral premotor and inferior/superior parietal cortices. The parietal region that was active during the writing of single letters spanned the border between the parietal superior and inferior lobuli.

In the "dot writing" task, significant fMRI activations were found in several brain regions, with obvious left-sided predominance. The clusters of activation with the most significant findings were revealed in the pericentral region, inferior parietal gyrus, middle cingulate and thalamus on the left side and, to a lesser extent, in the right inferior parietal and occipital cortices (Fig. 1). In the "letter writing" task, a more extensive activation was revealed throughout both cerebral hemispheres. In
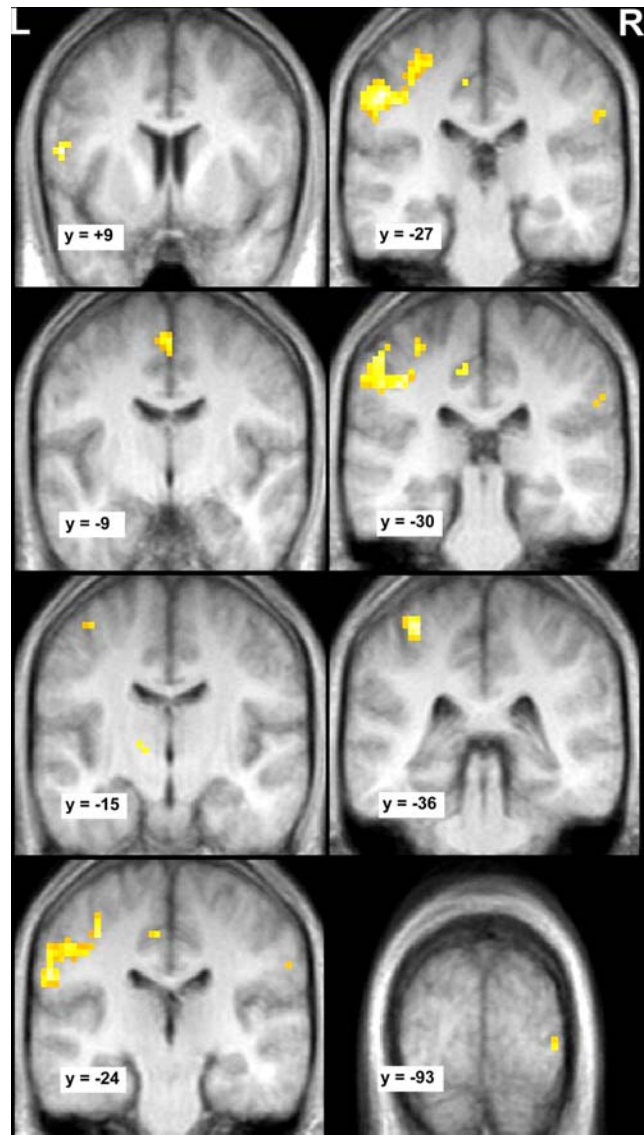


**Fig. 1** Group activation map for writing dots, overlapped on anatomical MR scans (mean of all volunteers). Images are carried out at a significance threshold of $P < 0.000005$ uncorrected. The significance of the reported peaks was verified using $P < 0.05$ corrected

**Fig. 2** Group activation map for writing letters, overlapped on anatomical MR scans (mean of all volunteers). Images are carried out at a significance threshold of $P < 0.000005$ uncorrected. The significance of the reported peaks was verified using $P < 0.05$ corrected
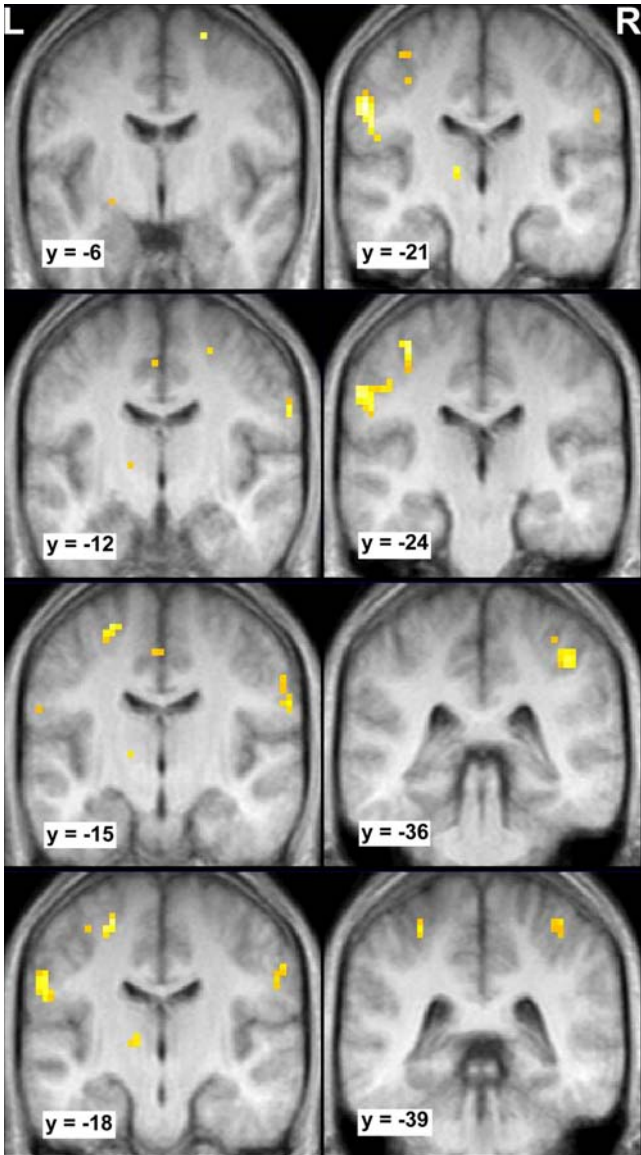
the left-sided structures, the pericentral region and inferior parietal gyrus were involved in the task performance, with the additional activation of the thalamic ventroposterolateral (VPL) and ventroposteromedial (VPM). The postcentral gyrus, inferior parietal and premotor regions were activated on the right side in this task (Fig. 2). Significantly, greater fMRI activations in the "letter writing" task (in comparison with the "dot writing" task) were found in the right-sided BA 37 (inferior occipital-temporal region) and superior parietal gyrus (BA 7) (Fig. 3). Table 1 summarizes the anatomical areas, their MNI co-ordinates, and statistical scores of the regions with significant activation in the investigated tasks.

## Discussion

This study was focused on brain regions specific for writing. First, we investigated repetitive movements in a self-paced paradigm. The movement was simple: making a dot with a pen. Self-initiated simple repetitive movements have often been used as an electrophysiological tool for investigating movement preparation and execution in the readiness potential (Bereitschafts potential; BP) protocol. The premovement potential is typically followed by movement accompanying potential; a complex potential, which is recorded during the movement (Rektor et al. 1998; Rektor 2003). In a series of direct intracerebral recordings BP cortical generators were consistently displayed in the contralateral primary motor and sensory cortices, and in the bilateral supplementary motor area (SMA) and motor cingulate areas; subcortical generators were observed in the basal ganglia and in the posterior thalamus. MAP was always recorded after BP, but it also occurred independently in the premotor and anterior parietal cortices. In this fMRI study, in connection with self-paced movement we observed significant changes in the left pericentral region on the convexity (BA 3, 1, 2, 4 and 40, 43), as well as in the mesial wall (BA 6, 31), and to a lesser extent at the right central convexity. This pattern corresponds to the electrical activity intracerebrally recorded in the BP/MAP protocol. Other fMRI studies of self-initiated movements have shown similar cortical activation patterns, specifically the activity in the lateral and mesial pericentral cortices in the hemisphere contralateral to the movement; findings in other regions were more variable (Ball et al. 1999; Maccotta et al. 2001; Newton et al. 2002; Cunnington et al. 2002, 2003). In this study, we were not able to uncover any significant subcortical activation, while in an fMRI study with rapid sequential finger movements, the haemodynamic changes were found in the putamen and midbrain (Cunnington et al. 2002), corresponding to the occurrence of BP and MAP generators in the basal ganglia (Rektor et al. 2001b). The movement used by Cunnington et al. differed from our protocol, and fMRI at 3T may be more sensitive. In any case, when comparing our fMRI study of a simple self-paced repetitive movement with intracerebral recordings of brain activity accompanying such movements, there is an evident overlap of results. This pattern of activation in our fMRI study covers regions that are known to participate in motor control: the primary sensorimotor cortex, the supramarginal gyrus, the SMA, and the underlying portion of the cingulate gyrus and the thalamus in the hemisphere contralateral to the movement.

The haemodynamic changes related to writing letters were more widespread than those related to writing simple dots. Writing letters in alphabetical order is a complex event, requiring the involvement of various systems. The movement itself is skilled. In comparison to writing dots, it is much more complex and variable.

**Fig. 3** Group activation map for differences between writing letters and dots, overlapped on anatomical MR scans (mean of all volunteers). Images are taken from ROI analysis (only right-sided BA 37 and BA 7 were included) with a significance threshold of $P < 0.05$ corrected (using contrast files masked with these right-sided Brodmann areas (BA) entering into the second level analysis)



z = 57    z = -15
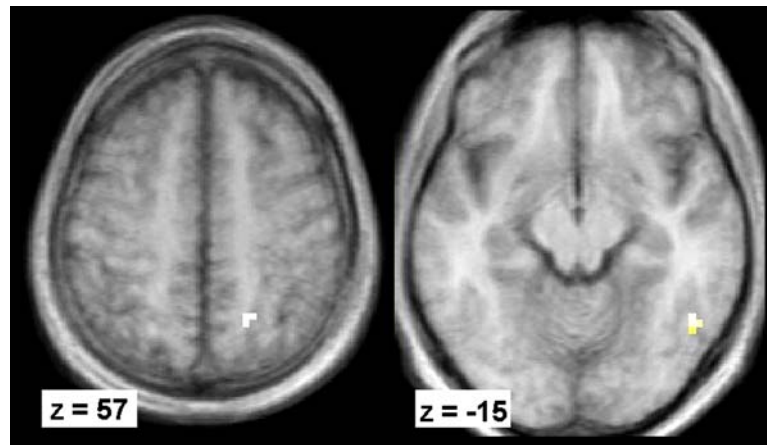
Moreover, writing letters in alphabetical order requires an increased attention load, procedural and working memory, and a putative brain network specific for writing. We found that in addition to the statistically significant changes observed in the pericentral cortices with left predominance, statistically significant changes were also observed in the bilateral premotor cortices, and in the inferior/SPL with right predominance. Not surprisingly, further clusters of activity were displayed in the right cerebellum, although these clusters were without statistical significance. A similar distribution of premotor and parietal activity has been described while writing names in Japanese *kana* letters (Katanoda et al. 2001). Premotor cortex (BA 6) activity was recorded in the superior frontal gyrus, and may be explained by an involvement of the higher order motor areas while performing this rather complex motor task. Premotor cortex mediates visuospatial information from intraparietal sulci and has been suggested to act as an extension of the dorsal visual pathway (Petit et al. 1996). The premotor activity in the left hemisphere may overlap with Exner's writing area, which is thought to contain a motor program for writing letters (Longcamp et al. 2003). The VPL and ventrointeromedial nuclei were active thalamic

**Table 1** Localization of significant activated areas

| | Brain region | BA | MNI co-ordinates | | | Z score | F score | Note |
|---|---|---|---|---|---|---|---|---|
| | | | x | y | z | | | |
| Dot | *Left hemisphere* | | | | | | | |
| | Postcentral | 2, 1 | -51 | −27 | 42 | 5.52 | 38.59 | |
| | Frontal inf. | 44 | -54 | 9 | 15 | 5.39 | 35.64 | |
| | Parietal inf. | 40 | -42 | −30 | 39 | 5.38 | 35.46 | |
| | Postcentral | 1, 2, 3 | -33 | −36 | 60 | 5.36 | 35.03 | |
| | Postcentral | 2 | -60 | −24 | 30 | 5.30 | 33.93 | |
| | Cingulate middle | 31 | -9 | −30 | 45 | 5.05 | 29.18 | |
| | Precentral | 4 | -33 | −27 | 57 | 4.96 | 27.70 | |
| | Thalamus VL | | −12 | −15 | 0 | 4.85 | 26.03 | |
| | SMA | 6 | 0 | -9 | 60 | 5.02 | 28.79 | |
| | *Right hemisphere* | | | | | | | |
| | Occipital inf. | 18 | 36 | -93 | -6 | 4.73 | 24.35 | |
| | Parietal inf. | 40 | 60 | -27 | 33 | 4.72 | 24.16 | |
| Alphabet | *Left hemisphere* | | | | | | | |
| | Postcentral | 1, 2 | -57 | -21 | 36 | 5.41 | 36.00 | |
| | Precentral | 4 | -36 | -24 | 57 | 5.12 | 30.48 | |
| | Premotor | 6 | -24 | -18 | 60 | 5.09 | 30.00 | |
| | Thalamus VPL/VPM | | -12 | -21 | 6 | 4.92 | 27.09 | |
| | Postcentral | 2 | -30 | -39 | 57 | 4.74 | 24.37 | |
| | SMA | 6 | -3 | -15 | 51 | 4.52 | 21.51 | * |
| | *Right hemisphere* | | | | | | | |
| | Parietal inf. | 40 | 42 | -36 | 48 | 5.00 | 28.37 | |
| | Postcentral | 2 | 63 | -12 | 30 | 4.95 | 27.68 | |
| | Premotor. | 6 | 21 | -6 | 69 | 4.95 | 27.64 | |
| Alphabet versus dot | *Right hemisphere* | | | | | | | |
| | Occipital inf./Temp. inf. | 37 | 48 | -57 | -15 | 4.36 | 19.53 | |

Standard $P = 0.05$ corrected. *Denotes non-significant result with $P < 3.07 \; 10^{-6}$ uncorrected
The comparison of Alphabet vs. Dot used an ROI analysis of the right-sided Brodmann areas (BA) 7 and 37, with a statistical threshold of $P < 0.05$ corrected

structures, i.e. structures acting as relay nuclei in sensorimotor control. Their activity may reflect an increased demand on sensorimotor integration in a writing task. The parietal region active with writing letters spanned the border between the parietal superior and inferior lobuli (BA 2, 40), deep in the intraparietal sulcus, with a surprising right-sided dominance. The parietal lobe, particularly the left superior parietal cortex (Menon and Desmond 2001) plays a critical role in writing. According to our study, it seems that the right parietal structures are also directly involved in writing letters. The right-sided SPL was highly active in writing tests with Japanese ideographs, in contrast with similar tests involving a phonological component. Matsuo et al. (2000) suggested that the visual references for handwriting movements may induce right SPL activation; however, in our task, the visual component was eliminated. The left and right intraparietal sulcus regions were active with grasping as well as with observation of a grasping movement. This may be related to the hand-object interaction (Grafton et al. 1996).

The direct comparison of the results of the two protocols was not significant with a confidence level of $P < 0.05$ corrected for whole brain volume. Thus, the ROI approach was used, and we tried to find significant differences within the two predefined ROI. The differences were found with a confidence level of $P < 0.05$ corrected for the volume of these predicted areas. The ROI were located in the posterior parts of hemispheres, in the ventral and in the dorsal visual pathway. There are indications of a possible involvement of the ventral extrastriate cortex in reading and writing (Roland and Gulyás 1994; Petrides et al. 1995; Garret et al. 2000; Nakamura et al. 2000; Flowers et al. 2004). Similarly, the SPL might be involved in writing. The role of BA 7 in visuospatial processing is well known (Stephan et al. 1995; Matsuo et al. 2000; Menon and Desmond 2001).

Evidently many regions, i.e. around the central sulcus, were active in both tasks, and the quantitative and spatial differences did not reach statistical significance. The two regions more active with writing were located in the posterior parts of the right hemisphere, the first one in the ventral temporo-occipital cortex, and the second one in the SPL. The involvement of those two areas might correspond to activity in the ventral and in the dorsal visual pathway. The most important difference was seen in the ventral temporo-occipital cortex (BA 37). The ventral extrastriate cortex is a part of the ventral visual pathway related to object recognition. A link between reading and writing and the ventral temporo-occipital cortex has been described already, but in the dominant hemisphere. The accuracy of distinguishing letters from non-letters was correlated with activity in left area 37 (Garret et al. 2000). In the posterior temporo-occipital cortex on the left side, a letter specific area in reading tests was identified (Flowers et al. 2004). Left BA 37 is active with writing and mental recall of *kanji* (Japanese ideographic characters, Nakamura et al. 2000) and writing words to dictation (Petrides et al. 1995). It is evident that alphabetical processing significantly enhances the left temporo-occipital cortex, namely BA 37. In our study, the writing of single letters activated the extrastriate visual cortex in the right hemisphere. There is another report indicating the involvement of the right-sided parieto-temporo-occipital region. A bilateral BA 37 increase of activity was described in writing to dictation was when compared with verbal tasks (Petrides et al. 1995). The right BA 7 and bilateral BA 37 were active in a mirror-image task indicating the importance of these regions in spatial cognitive processing (Alivisatos and Petrides 1997). A nearby region, the border between the inferoparietal lobule and the occipital lobe was activated in both the left and right hemispheres, by a *kanji* puzzle task (Matsuo et al. 2001) that required subjects to refer to the displayed characters, and demanded intensive correspondence between visuospatial analysis and the handwriting movements. The temporo-occipital association areas have been suggested to subserve visual imagery (Roland and Gulyás 1994). Our results may indicate that the posterior temporal-parietal-occipital region is involved not only in object recognition, but also in the composition of letters without visual control and without visual feedback. It is likely that visuospatial imagery may have played an important role in our task.

The involvement of the right SPL (BA 7) in writing may be explained by the well-known role of SPL in visuospatial processing. Right and left SPL are involved in *kanji* writing (Matsuo et al. 2000) and left SPL plays a role in writing to dictation (Menon and Desmond 2001). It was suggested that the right SPL activation might be related to writing visually presented orthographic material. This area was less activated in phonologically induced writing than in copying letters (Matsuo et al. 2001). The right SPL, including the intraparietal sulcus, was one of the regions significantly active in Japanese *kana* (phonographs) mirror reading as compared to normal reading. It has been proposed that this region is a "special area, which is involved in co-activated networks of visuospatial transformation during mirror reading," (Dong et al. 2000). Visual references for handwriting may be involved but cannot fully explain the right SPL activity, because in our study no visual presentation and no visual control were present. This arrangement of our study also excluded the potential influence of oculomotion on the haemodynamic changes in the intraparietal sulcus region. On the other hand, BA 7 is involved in motor imagery. In a PET study, there was a significant increase of regional blood flow in the superior and inferior parietal lobules bilaterally when imagined movements were compared with motor preparation (Stephan et al. 1995). The right SPL might play a role in visual imagining of letters. Our recordings indicate that the right intraparietal sulcus region is involved in elemental processes linked with letter recognition and production.

In this study, we identified several brain regions that are active during the writing of single letters. While the

premotor-parietal co-activation is not surprising, the specific involvement of the posterior parts of the hemisphere is a new element. We conclude that the posterior parts of the right hemisphere play a role in writing. Dorsal visual pathways in and around the intraparietal sulcus, as well as the ventral pathway in the ventral temporo-occipital cortex are active while the elemental writing component single letters are produced. The right hemisphere is dominant for tasks requiring manipulation in space. It is possible that activation of this region is linked with the spatial dimension of the writing. Writing letters is a rather elemental test, minimally loaded with semantic or phonological aspects. This study was performed without visual control and the demand on orientation in space and spatial imagination was rather high. The right-sided parietal cortices may play an important role in the elemental mechanism of writing.

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