

Short communication

Left superior parietal cortex involvement in writing: integrating fMRI with lesion evidence

V. Menon^{a,b,*}, J.E. Desmond^{c,d}

^aDepartment of Psychiatry & Behavioral Sciences, Stanford University School of Medicine, Stanford, CA 94305, USA

^bProgram in Neuroscience, Stanford University School of Medicine, Stanford, CA 94305, USA

^cDepartment of Psychology, Stanford University School of Medicine, Stanford, CA 94305, USA

^dDepartment of Radiology, Stanford University School of Medicine, Stanford, CA 94305, USA

Accepted 15 May 2001

Abstract

Writing is a uniquely human skill that we utilize nearly everyday. Lesion studies in patients with Gerstmann's syndrome have pointed to the parietal cortex as being critical for writing. Very little information is, however, available about the precise anatomical location of brain regions subserving writing in normal healthy individuals. In this study, we used functional magnetic resonance imaging (fMRI) to investigate parietal lobe function during writing to dictation. Significant clusters of activation were observed in left superior parietal lobe (SPL) and the dorsal aspects of the inferior parietal cortex (IPC) bordering the SPL. Localized clusters of activation were also observed in the left premotor cortex, sensorimotor cortex and supplementary motor area. No activation cluster was observed in the right hemisphere. These results clearly indicate that writing appears to be primarily organized in the language-dominant hemisphere. Further analysis revealed that within the parietal cortex, activation was significantly greater in the left SPL, compared to left IPC. Together with lesion studies, findings from the present study provide further evidence for the essential role of the left SPL in writing. Deficits to the precise left hemisphere parietal cortex regions identified in the present study may specifically underlie disorders of writing observed in Gerstmann's syndrome and apractic agraphia. © 2001 Elsevier Science B.V. All rights reserved.

Theme: Neural basis of behavior

Topic: Cognition

Keywords: fMRI; Writing; Parietal cortex; Superior parietal lobe; Agraphia; Gerstmann's syndrome; Exner's area

Writing is a uniquely human skill that we utilize nearly everyday. Most of our knowledge of brain areas involved in writing has come from lesion studies in patients with neurological disorders. Agraphia, or impairment in the inability to write in the absence of other motor abnormalities, may take several symptomatic forms and can arise from disruption to any component of brain systems mediating writing. A review of lesion studies reveals that specific aspects of writing can be selectively impaired by localized brain damage to the superior parietal lobe, supramarginal gyrus, angular gyrus, Wernicke's area, or Broca's area [13]. More specifically, agraphia is one of the

classical features of Gerstmann's syndrome that accompanies injury to the parietal cortex. A majority of these studies have, however, implicated the parietal cortex in pure agraphia, a form of agraphia characterized by writing disorders in the absence of other motor and language abnormalities. While lesion studies have suggested that the parietal lobe plays a critical role in writing, very little information is available about the precise anatomical location of the lesions underlying Gerstmann's syndrome. Further, there have been very few investigations of writing in normal healthy controls. The overall aim of this study was to investigate parietal cortex involvement in writing in normal healthy subjects using functional magnetic resonance imaging (fMRI). In addition to demarcating more precisely the parietal cortex regions involved in writing, we also directly examined regional and hemispheric differences in brain activation in the superior and inferior

*Corresponding author. Tel.: +1-650-498-6737; fax: +1-520-244-6474.

E-mail address: menon@stanford.edu (V. Menon).

parietal cortex. To our knowledge, this is the first functional brain imaging study of writing to dictation.

Fourteen healthy, right-handed native English speakers (8 males and 6 females; ages 18–32 yrs) participated in the study. The task consisted of 12 alternating 40s writing and passive fixation epochs. In the writing epoch, subjects wrote short dictated sentences, which were presented binaurally via the scanner's internal speaker. The sentences were well-known aphorisms such as "The pen is mightier than the sword". The auditory presentation lasted less than 5 s. Subjects lay supine in the scanner and wrote in small letters in a restricted area (about 10×10 cm) of a sheet of paper placed on their right thigh. Subjects rewrote the sentence if they completed writing it before the end of the 40 s epoch, at which point they were instructed to stop writing.

During task performance, 10 axial slices (resolution: 4.35×4.35×6 mm³), roughly extending 5 to 65 mm superior to the anterior and posterior commissure (AC–PC) axis were acquired using a T2* weighted gradient echo spiral pulse sequence (TR=1000 ms, TE=40 ms, flip angle=40° and 4 interleaves) [7]. To aid in localization of brain activation, high-resolution T1-weighted image (TR=24 ms; TE=5 ms; flip angle=40°; 24 cm field of view; 124 slices in sagittal plane; 256×192 matrix; acquired resolution=1.5×0.9×1.2 mm) were also acquired. fMRI data were analyzed using techniques implemented in SPM97 (Wellcome Department of Cognitive Neurology), including motion correction, spatial normalization, and spatial smoothing (FWHM=6 mm) [6,15]. For each subject, brain activation related to writing was determined by contrasting the writing and fixation epochs. A random effects model [8] was then used to determine precise brain areas that showed significant group activation during writing. Analysis of variance (ANOVA) was used to directly compare brain activation in two regions of interest (ROIs) in the parietal cortex: the superior parietal lobe (SPL) consisting of Brodmann areas (BA) 5 and 7, and the inferior parietal cortex (IPC) consisting mainly of BA 39 and 40. Separate ROIs were constructed in each hemisphere using known neuroanatomical surface and cross-sectional MRI landmarks [4,14].

Voxel-by-voxel analysis of group data revealed several significant clusters (height threshold $P<0.01$; corrected for multiple spatial comparisons at the $P<0.01$ level) of activation in the left SPL and IPC as well as the premotor and sensorimotor cortices (Table 1; Fig. 1). Notably, no significant clusters were detected in the right hemisphere (Fig. 1).

We then directly compared activation in the SPL and IPC by a 2-way ANOVA, using within-subjects factors of ROI (SPL, IPC) and Hemisphere (Left, Right). The percentage of voxels activated above a specified threshold ($Z>2.33$; $P<0.01$) in each ROI was used as the measure of activation. The analysis revealed a significant effect of ROI (SPL>IPC; $F(1,13)=14.6799$, $P=0.0020$) and Hemisphere (Left>Right; $F(1,13)=29.72914$, $P=0.0001$). No significant interaction was observed between ROI×hemisphere ($F(1,13)=0.3679$, $P=0.5545$). Lowering the threshold to $Z>1.67$ ($P<0.05$) also did not reveal significant clusters of activation in the right hemisphere.

This is the first study to examine brain activation during writing to dictation in English or any other language. Significant clusters of activation were detected in the left, but not the right, hemisphere. Our study clearly demonstrates the involvement of the left superior parietal lobe in writing. Intriguingly, although the writing task involves a strong visuo-spatial component, no activation was detected in the right SPL. This is particularly surprising given the low-level baseline condition used in the present study. One possible explanation for the lack of right SPL is that our task did not involve visually guided writing. These results suggest that brain systems that support writing, including the visual-spatial components involved in this process, are primarily localized to the language-dominant hemisphere. These findings are in agreement with observations based on lesion studies of agraphia, which have generally pointed to the language dominant hemisphere as being critical for writing [13].

Our findings are consistent with lesion studies, which have consistently pointed to the left parietal cortex in agraphia. Results from the present study may help to more precisely localize parietal cortex regions involved in Gerstmann's syndrome. Since the pioneering neurological

Table 1
Brain areas that showed significant activation during writing to dictation^a

Activated regions	Cluster level significance	Talairach coordinates	# of voxels	Maximum Z Score
Sup. & Inf. Parietal Cortex (BA 7/40) Postcentral Gyrus (BA 1, 2, 3) Precentral Gyrus (BA 4)	<0.001	−22, −12, 50	2353	5.43
SMA (BA 6)/ Cingulate Cortex (BA 24)	0.005	−2, −4, 54	641	4.83
Premotor cortex (BA 6)	0.028	−52, −2, 30	378	3.99

^a Each cluster was significant after corrections for multiple spatial comparisons ($P<0.01$).

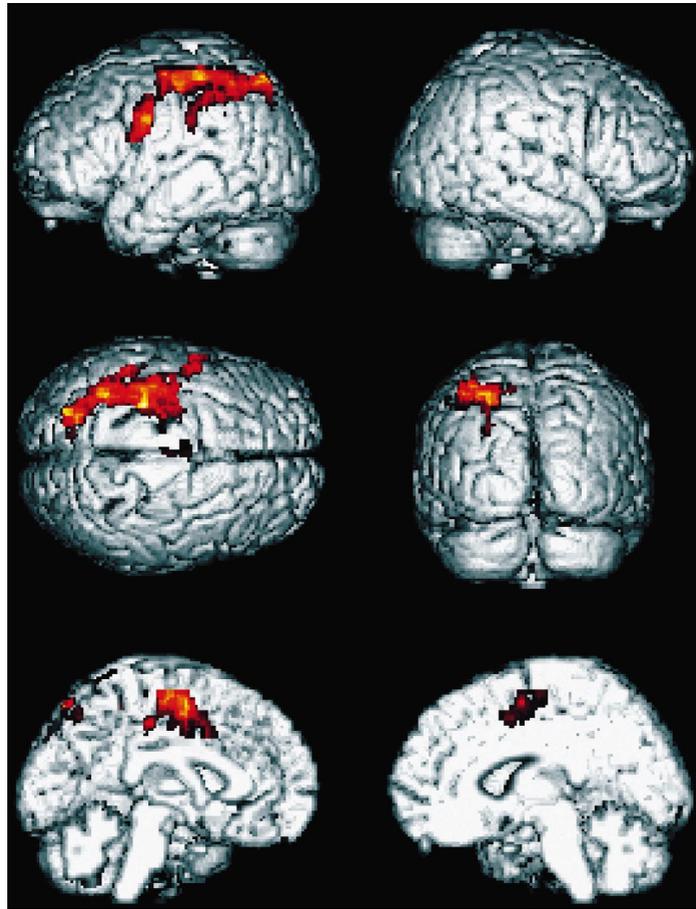


Fig. 1. Surface rendering of brain areas that showed significant activation during writing to dictation. Activation was localized to the superior and inferior parietal cortex, supplementary motor cortex, premotor cortex and sensorimotor cortex in the left hemisphere. No significant activation clusters were observed in the right hemisphere. Results are from a random effects analysis of activation in 14 subjects; each activated cluster was significant after corrections for multiple spatial comparisons ($P < 0.01$).

studies of Ogle [11], it has been well documented that writing involves three key several component processes: motor control, language processing and production, and visuo-spatial mapping and coordination. Imaging studies have implicated the left supramarginal and left angular gyri of the IPC in language and lexical processing and the right SPL in visual-spatial processing [3]. In comparison, little is known about the function of the left SPL. In the present study, not only was activation greater in the left SPL, compared to the right SPL, the left SPL activation was also significantly greater than the left IPC activation. These results suggest that the left SPL plays an important role in writing. Matuso et al. [10] have recently shown that the left as well right SPL are involved in writing Kanji, although left hemisphere activation tended to be greater than right hemisphere activation. The right SPL activation may be related to writing visually presented orthographic material. This study did not, however, provide a direct comparison of left versus right hemisphere activation.

In further interpreting our results, it is particularly interesting to examine the precise deficits in writing that

arise from lesions to the left SPL. A number of studies have consistently shown that lesions to the left SPL results in apractic agraphia, an impairment in which the actual orthographic production of letters and words is abnormal despite normal sensorimotor function, visual feedback, and word and letter knowledge [1,2,12]. For example, Otsuki et al. [12] recently demonstrated a case of pure agraphia in a Japanese male after a haemorrhage in the left SPL in which the patient developed difficulty in letter formation but showed no linguistic errors. Furthermore, this patient manifested a selective disorder of writing Kana stroke sequences, even though he could orally state the order in which correct sequence of strokes should proceed. This suggests that the left SPL plays an important role in the sequential execution components of writing. Damage to the left SPL may affect writing either due to loss of appropriate spatial and kinesthetic modulation of movements [1] or due to memory deficits for sequential motor movements associated with writing letters [9]. Together with findings from the present study, these observations provide further evidence for the essential role of the left

SPL in writing both graphemic and non-graphemic languages.

Finally, we note that significant activation was also observed in the left premotor and left motor cortex in a region inferior and anterior to the primary focus of the hand area of the sensorimotor cortex. This region may overlap with Exner's area, a region that has been associated with motor deficits specifically related to writing ([13,5]). Future studies will investigate the involvement of this and other prefrontal and temporal cortex regions in writing. Future studies will also utilize additional control conditions to further elaborate the specific contributions of different brain regions, including the left parietal cortex, to writing.

Acknowledgements

Supported by NIH grant HSD40761, a NARSAD Young Investigator Award and a grant from the Norris Foundation to VM. It is a pleasure to thank Robert Anagnoson and Ben Kraznow for assistance with data analysis.

References

- [1] M.P. Alexander, R.S. Fischer, R. Friedman, Lesion localization in apractic agraphia, *Arch. Neurol.* 49 (3) (1992) 246–251.
- [2] S.H. Auerbach, M.P. Alexander, Pure agraphia and unilateral optic ataxia associated with a left superior parietal lobule lesion, *J. Neurol. Neurosurg. Psychiatry* 44 (5) (1981) 430–432.
- [3] R. Cabeza, L. Nyberg, Imaging cognition II: An empirical review of 275 PET and fMRI studies, *J. Cogn. Neurosci.* 12 (1) (2000) 1–47.
- [4] H.M. Duvernoy, *The Human Hippocampus: Functional Anatomy, Vascularization and Serial Sections With Mri*, Springer, NY, 1998.
- [5] S. Exner, *Untersuchungen über Die Lokalisation Der Funktionen in Der Grosshirnrinde Des Menschen*, Braumuller, Vienna, 1881.
- [6] K.J. Friston, A.P. Holmes, K.J. Worsley, J.P. Poline, C.D. Frith, R.S.J. Frackowiak, Statistical parametric maps in functional imaging: A general linear approach, *Hum. Brain Map.* 2 (1995) 189–210.
- [7] G.H. Glover, S. Lai, Self-navigated spiral fMRI: interleaved versus single-shot, *Magn. Reson. Med.* 39 (3) (1998) 361–368.
- [8] A.P. Holmes, K.J. Friston, Generalisability, random effects & population inference, *Neuroimage* 7 (4) (1998) S754.
- [9] N. Kapur, N.F. Lawton, Dysgraphia for letters: a form of motor memory deficit? *J. Neurol. Neurosurg. Psychiatry* 46 (6) (1983) 573–575.
- [10] K. Matsuo, T. Nakai, C. Kato, T. Moriya, H. Isoda, Y. Takehara, H. Sakahara, Dissociation of writing processes: functional magnetic resonance imaging during writing of Japanese ideographic characters, *Brain Res. Cogn. Brain Res.* 9 (3) (2000) 281–286.
- [11] J.W. Ogle, *Aphasia and Agraphia*. Report of the Medical Research Council of St. George's Hospital, London, Vol. 2, 1869, 83–122.
- [12] M. Otsuki, Y. Soma, T. Arai, A. Otsuka, S. Tsuji, Pure apraxic agraphia with abnormal writing stroke sequences: report of a Japanese patient with a left superior parietal haemorrhage, *J. Neurol. Neurosurg. Psychiatry* 66 (2) (1999) 233–237.
- [13] D.P. Roeltgen, *Agraphia*, in: E. Heilman (Ed.), *Clinical Neuropsychology*, Oxford University Press, New York, 1993, p. 66.
- [14] J. Talairach, P. Tournoux, *Co-planar Stereotaxic Atlas of the Human Brain*, Thieme Medical Publishers, New York, 1998.
- [15] K.J. Worsley, K.J. Friston, Analysis of fMRI time-series revisited-again, *Neuroimage* 2 (3) (1995) 173–181.