Neural representation of an alphasyllabary – the story of Devanagari

T. Das[1], U. Kumar[1], R. S. Bapi[2], P. Padakannaya[3] and N. C. Singh[1,*]

[1]National Brain Research Centre, NH-8, Nainwal Mode, Manesar 122 050, India
[2]Department of Computer and Information Sciences, University of Hyderabad, Hyderabad 500 046, India
Department of Psychology, University of Mysore, Mysore 570 006, India

We used functional brain imaging to study brain activation patterns when 16 native speakers read phrases in Devanagari, a writing system with alphabetic and syllabic properties. We found activation in the left insula, fusiform gyrus and inferior frontal gyrus, as seen for reading alphabetic scripts and in the right superior parietal lobule as associated with reading syllabic scripts. Additionally, we found bilateral activation in the middle frontal gyrus (Lt. BA 46, Rt. BA 6/44) which we attribute to complex visuo-spatial processing required for reading Devanagari, wherein consonants are placed linearly from left to right and vowels positioned non-linearly around them.

Keywords: Alphabetic, Devanagari, syllabic, fMRI, Hindi.

THE cortical activation underlying representations of different orthographies has been a subject of great interest for researchers of language and neuroscience. Because writing systems may be classified as alphabetic[1], syllabic[2] or logographic[1], a basic question of investigation is – does there exist a unified orthographic processing system for different scripts or are there distinct processing systems? Orthographic variation across scripts is not uncommon and scripts have their own characteristics and presentations[1]. Korean, for example, is rather complex in that it is written in a mixture of three scripts[3]: an alphabetic syllabary called *hangul*, Chinese characters called *hanja*, and the Latin alphabet called *romaja*. Japanese is written in a mixture of four scripts[2]: *kanji* (Chinese characters), two syllabic scripts called *hiragana* and *katakana*, and *romaji* (the Latin alphabet). English, which uses the Roman script, is alphabetic, has vowels and consonants that are written linearly from left to right.

A host of studies on word recognition in various writing systems like Chinese[4], Japanese[5], Korean[6] and English[7] have shown the activation of a common cortical network, primarily in the left hemisphere for all scripts. Additionally, these studies have also shown that for complex scripts like Chinese[4], Korean[6] and Japanese kana[5], there is bilateral activation wherein activation in the right hemisphere has been attributed to the processing of complex visuo-spatial information. In addition, these imaging studies have also shown that tasks which require reading alphabetic scripts are associated with increased activation, primarily in the left hemisphere and involve a network of areas, each of which may be activated to a different degree depending upon specific task demands. This network of areas includes the basal surface of the temporal lobe, the posterior portion of the superior and middle temporal gyri extending into temporo-parietal areas (supramarginal and angular gyri), and inferior frontal lobe areas of the left hemisphere[8–10]. The alphabetic system is linear in structure and is based on the phoneme to grapheme association. Chinese characters, on the other hand, are a striking contrast to alphabetic scripts because their graphic units represent morphemes (meaning-bearing syllables) and are square and nonlinear in structure. Early studies on the Chinese writing system showed the right cerebral hemisphere to be more effective in processing Chinese[11]. However, later studies questioned this claim and reported that the reading of Chinese characters is bilateral with activation in the left hemisphere similar to that seen for alphabetic scripts accompanied by activation in the right hemisphere mainly in BA 8 (ref. 12).

Similar studies conducted with Korean[6] language, which uses both alphabetic Korean words and logographic Chinese words in its writing system, also showed activation similar to alphabetic and Chinese scripts along with activation in the right prefrontal cortex (BA 8) and left prefrontal cortex (BA 46; ref. 6). A study on Japanese *kana*, a syllabic script, on the other hand showed activation similar to alphabetic scripts accompanied by superior parietal cortex and cerebellar activation in the right hemisphere[5].

There have been no fMRI studies so far on the neural representations of alphabetic-syllabic scripts like Devanagari, an ancient writing system widely used in south Asia. In Devanagari, consonants are written in a linear left-to-right order and vowel signs are positioned nonlinearly above, below, or to either side of the consonants. As a result for certain words in Devanagari, the vowel precedes the consonant in writing but follows it in speech. Hindi, which is an example of Devanagari, therefore presents itself as a unique case for investigation.

*For correspondence. (e-mail: nandini@nbrc.ac.in)

Hindi is an Indo-Aryan language that uses Devanagari, an alpha-syllabic orthographic system widely used in south Asia. A number of languages in the Indian subcontinent today are derived from a single script, namely Brahmi, which emerged during the 3rd century in the Ashoka inscriptions and has a Semitic source possibly dating as far back as the 5th century BC[13]. Languages written in Devanagari script include Nepali, Marathi, Bengali, Gujarati, Hindi, Tibetan and Burmese. The Devanagari system originated as the script used to write down Sanskrit. It consists of 48 basic letters and additional diacritical signs that together represent every sound of the Sanskrit language[14]. The arrangement of the alphabet is strictly phonetic, with letters classified by place of articulation: vowels and diphthongs first, then consonants with an inherent implicit schwa vowel. In Devanagari, consonant letters are used to represent both the consonant and schwa, unless marked otherwise. Devanagari has syllabic and alphabetic properties. It differs from other alphabetic scripts in that each consonant in Devanagari has an inherent associated vowel. Further, it differs from purely syllabic writing systems in that it does not employ unique symbols for distinct syllables[15]. The basic phonological unit that corresponds to a grapheme in Hindi is an *akshara* that is always a syllable. For an alphabetic language like English, this is a phoneme. These *aksharas* in written form contain one or more consonant(s) and vowels that are often symbolically attached to each other by *matras*. These matras often precede and follow the core consonant and have an impact on visual manipulation of phonological units[15]. A single *akshara* can consist of three or four symbolic attachments of different sounds on a single base representation, making this a complex reading system (examples in Appendix 1).

Research on reading in Indo-Aryan languages[15,16] has indicated the relevance of script-specific features in processing written languages like Devanagari as opposed to English or French. Studies on segmentation in Devanagari by native Hindi speakers have shown how alphasyllabic nature of the script influences one's performance[15]. As Devanagari presents a mixture of syllabic and alphabetic scripts, the main aim of this study is to see whether participants who perform a silent reading task in Hindi show cortical activation similar to those seen for both alphabetic and syllabic scripts or distinct from them.

Participants

Sixteen native Hindi speakers (mean age 29 years, SD = 4.69; 9 males and 7 females), selected from a large pool of such speakers, participated in this study. All the participants were graduates or postgraduates who had undergone at least 10 years of education in Hindi. None of them had any history of medical, neurological or psychiatric illness. They were all right-handed on the Edinburgh Handedness Inventory[17]. All the participants gave written informed consent for experimental procedures, approved by the Institutional Human Ethics Committee of the National Brain Research Centre, India.

Stimuli and experimental design

Brain activity, associated with phrase reading was examined using a block design. The experiment consisted of silent reading of the Hindi language text. Each reading task and rest condition lasted 20 s. During rest condition, which was used as the baseline control condition, participants were instructed to look at a fixation-cross. In each reading task, a section of text consisting of three word phrases was displayed on the screen (as shown in example stimuli in Appendix 1) and the participants were requested to read the phrases silently.

During each 20 s experimental epoch, a new phrase stimulus was shown in the centre every 5 s. Thus, a total of four new phrases were shown during every reading task period and the sequence and order of presentation of the phrase stimuli were randomly shuffled among the participants. Each participant read 16 phrases in a single run and completed two such runs.

Image acquisition

Scanning was conducted on a 3 Tesla Phillips MRI scanner equipped with echo planar imaging (EPI) and a standard head coil for radio frequency transmission and signal reception. To restrict head movement and motion artefacts, the participant's head was fixed by foam cushions and ear clamps positioned behind the neck and around the head. Participants were also instructed to keep their head as still as possible. Headphones customized for fMRI experiments were inserted into the head coil and provided isolation from scanner noise. The room lights were dimmed for all conditions.

Stimuli were retro-projected onto a screen outside the scanner and a head mounted apparatus in the scanner. The presentation of written words was controlled by E-prime software (Psychology Software Tools, Inc., USA) running on an IBM-compatible computer located outside the scanner. High-resolution structural T1-weighted images covering the whole brain were acquired from all participants for anatomical localization. Functional images were acquired using a T2-weighted echo-planar sequence at 30 axial slices parallel to the AC–PC plane. (TR/TE = 2 s/35 ms, flip angle 90°, field of view 230 mm with 64×64 image matrix, yielding an in-plane resolution of 3.59×3.59 mm. Slice thickness 4 mm with 1 mm gap.) A total of 160 volume images were acquired.

Statistical analysis

The imaging data were analysed using statistical parametric mapping (SPM5 developed by Welcome Department of Cognitive Neurology, London). The functional images were reoriented to set the origin near the intersection of the coronal plane through AC and the AC–PC line and then motion correction was performed with respect to the first functional image in each session. Anatomical image for each subject was co-registered with the first functional image and then normalized to the T1 template from the International Consortium for Brain Mapping (ICBM) Project. The resulting parameters were used for normalizing all the functional images[18] into Talairach stereotaxic space[19]. Spatial smoothing with a Gaussian kernel of 8 mm FWHM and temporal filtering (Gaussian low pass filter with 4 mm full-width at half maximum) was applied to the normalized images. The pre-processed data were analysed using the general linear model framework[20]. For each participant, the experimental settings (language task versus fixation) were modelled using boxcar functions convolved with the canonical hemodynamic response function. The resulting *t*-maps (SPM $\{t\}$) from each participant were taken into a second level analysis.

Group analysis was performed using the random effects approach[21] as implemented in the SPM5 software. Contrast images computed from the subject-specific models were entered into a one-sample *t*-test at the second level. The voxel coordinates reported in the tables were transformed[22] from MNI to Talairach space. Locations of peak activation are reported in Table 1 for various regions. Statistical thresholding at a significance level of $p < 0.001$ (uncorrected) was applied for determining significant activations and to reduce the effect of type I error (spurious activation related to motion or other systematic error), a 10-voxel clustering (spatial-extent) threshold was applied so that only clusters consisting of 10 or more contiguous activated voxels were considered significant. Brain activation results at selected cortical and sub-cortical areas were overlaid on the T1 template provided in SPM5. 3D-rendered images of the activated clusters are shown on the single-subject render file available in SPM5.

Results

Figures 1 and 2 display the hemodynamic response obtained from the task epochs of two runs as indexed to the fixation baseline. The coloured areas comprise the significantly activated voxels averaged across subjects and measurement periods, as compared to the baseline condition. Table 1 shows the results of statistical analysis of the fMRI measurements representing anatomical area, Brodmann area and *t*-values.

Our results showed that the brain regions activated during the Hindi reading task were located bilaterally in the frontal and occipital lobes. In the left hemisphere, we found activation in the fusiform gyrus (BA 37), middle frontal gyrus, supplementary motor area, cerebellum and insula (BA 13) as seen for alphabetic writing systems (see Table 1; Figures 1 and 2). In the right hemisphere, activation was seen in the superior parietal lobule and cerebellum, similar to that seen in syllabic scripts[5]. In addition, we also observed activation of the middle frontal gyrus (Rt. BA 6/44 and Lt. BA 46) in our experiment, a region also observed in the processing of logographic scripts[6]. In line with other studies on reading words and sentences[23–26], we also observe activation in the left fusiform gyrus (BA 37). Activation in the left fusiform gyrus during word reading was first reported by Posner and Petersen[27]. Subsequently, a number of studies on word and sentence reading in scripts including Chinese, Japanese *kana* and Korean *hangul* have also reported the activation of this area during reading[6,28,29]. Meta-analyses of word reading studies[30,31] also confirmed the activation of the left fusiform gyrus and it is now referred to as the visual word form area (VWFA). For Devanagari too, we confirm the activation of the BA 37 and we attribute its activation to the processing of words in Hindi/Devanagari.

Table 1. Group activations during silent Hindi phrase reading task

Anatomical area	Brodmann area	Coordinate (*x*, *y*, *z*)	*t* value
Left cerebellum		–44, –65, –19	5.53
Right cerebellum		40, –61, 20	4.49
Right occipital lobe, Cuneus	18	26, –95, –2	10.52
Left fusiform gyrus	37	–42, –57, –11	5.87
Right insula	13	40, 16, 8	5.32
Left insula	13	–34, 24, 17	5.04
Right supplementary motor area	6	0, 5, 57	4.77
Right middle frontal gyrus	6/44	53, 10, 40	8.82
Left middle frontal gyrus	46	–46, 27, 26	4.26
Left inferior frontal gyrus	47	–34, 19, –6	4.57
Right superior parietal lobule	7	34, –57, 54	4.22
Right inferior parietal lobule	40	63, –45, 39	5.04

Coordinates of peak activation are reported for regions having at least 10 significant voxels.

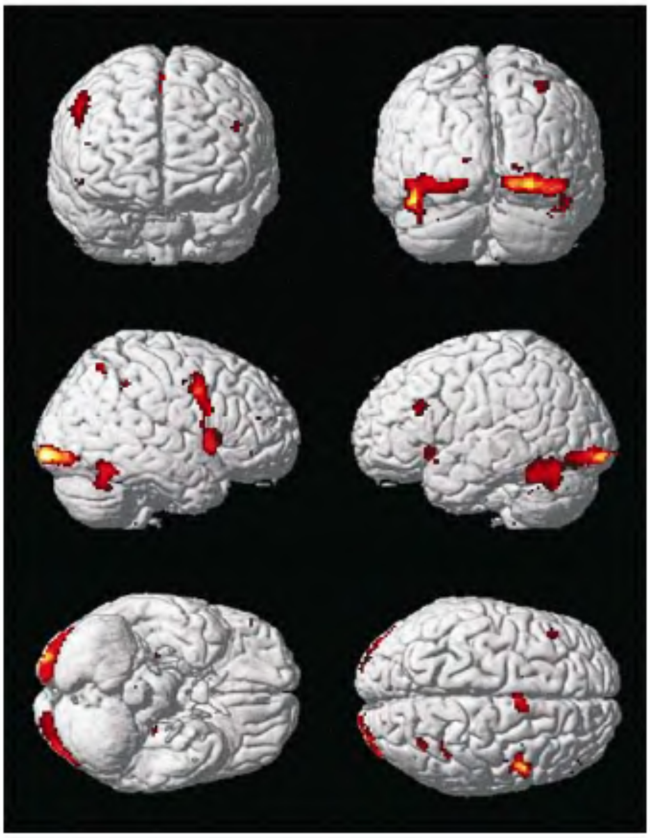

Figure 1. Brain regions with significant activity during silent reading of Hindi phrases versus fixation (group analysis results; voxel-wise threshold of uncorrected $p < 0.001$, with extent of threshold $k = 10$).

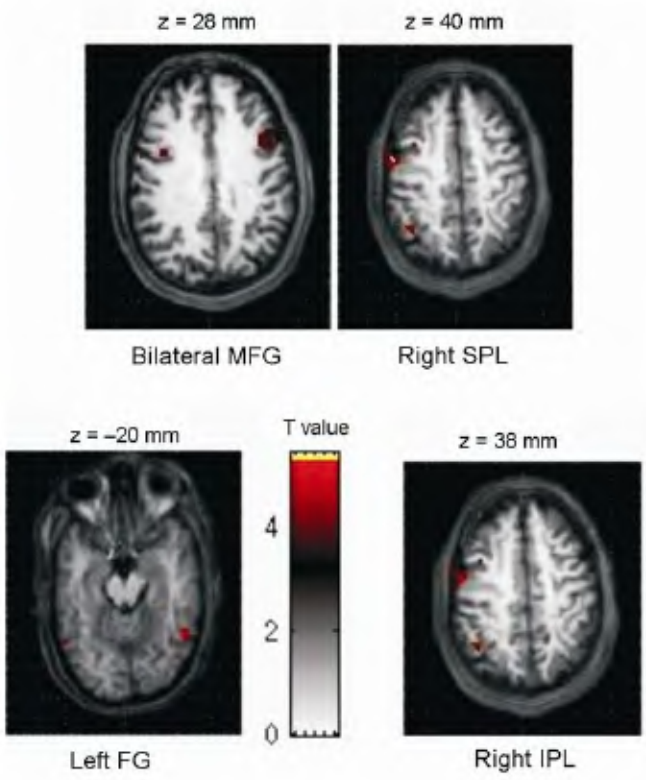

Figure 2. Slices showing group activation map. Bilateral middle frontal gyrus, right superior-parietal lobule, left fusiform gyrus and right inferior-parietal lobule.

Discussion

In this study, we investigated the phrase processing of 16 native Hindi speakers reading Devanagari using a silent reading task. Phrase processing is more complex than single word processing. A number of fMRI studies have reported that the semantic processing of a written phrase produces more intense blood oxygenation level dependency signals in the right occipito-temporal areas than the left occipital region[33]. Our observations of activations in the right hemisphere are in agreement with the previous studies that have indicated right hemisphere dominance for perception and semantic processing[12]. The other noteworthy result is the activation of the middle frontal gyrus/area (Rt. BA 6/44 and Lt. BA 46) in our experiment. In earlier fMRI studies of reading logographic characters, activation in BA 46 was observed[6]. In the case of Devanagari too we find activation in the middle frontal areas (Rt. BA 6/44 and Lt. BA 46). We therefore suggest that the middle frontal area may be recruited as a common region in processing complex visuo-spatial information while reading.

The inferior frontal activation is also of interest. The role of the inferior frontal lobe for reading different scripts and its differential role in phonological and semantic tasks is a subject of debate. For the Devanagari script where a consistent grapheme to phoneme association has been suggested[15], we postulate that the inferior frontal lobe mediates semantic processing which may play a role in grapheme–phoneme mapping. Activation of the cerebellum is supported by the view that it is engaged during reading and differentially activates in response to phonological and semantic tasks. These results provide increased support to the view that cerebellum contributes to the cognitive processes integral to reading[33].

Activations of inferior parietal lobule (IPL) and insula were also observed. The role of dorsal IPL has been posited as part of a general attentional network[34,35]. Additionally, it is also believed to be crucial for retaining temporal order information[36], attention switching[37] and task preparation[38] – all domain general functions that involve working memory. However, the ventral IPL (VIPL) has been shown to have a preference for verbal working memory, more so, when the task is phonological[39]. Thus, VIPL is associated with a phonological encoding–recoding process (phonological short term store) central to a variety of language tasks[30]. Although the role of the inferior parietal region for word reading is still not clear[40], we suggest that the activation of inferior parietal lobe might have resulted from phonological maintenance during phrase processing. The activation in superior parietal lobule (BA 7) seems to play a specialized role in languages, which are syllabic, i.e. Japanese *kana*[5] and appears to play a significant role for visually guided motor tasks and disengaging attention from locations in visual space[41]. As Hindi is also syllabic, we also attribute a similar role for BA 7 while reading Devanagari.

The insula on the other hand not only plays a role in the production or motor aspects of language, but has also been shown to participate in processes relevant to articulatory sequencing[42]. In Devanagari, for certain words, the vowel precedes the consonant in writing but follows it in speech (हिन्दी, for example). Reading such words calls for articulatory sequencing, which we suggest may be accomplished by the insula and explains its activation only for Hindi and not English.

In conclusion, the investigation of cortical activation during the perception of visually presented phrases by native Hindi speakers provided an excellent chance to explore the neural representations of a hitherto unexplored writing system, namely Devanagari script (of which Hindi is an example) which not only has features of both alphabetic and syllabic scripts but is unique in its complex spatial arrangement of vowels around consonants. Our results show that true to its nature, Devanagari exhibits activation patterns that correspond to brain regions, which are related to both syllabic and alphabetic writing systems, namely temporo-parietal, inferior-parietal lobule seen for alphabetic systems and the superior-parietal lobule seen in syllabic writing systems. Therefore, Devanagari presents a novel example of a complex script, which places increased demands on visuo-spatial processing. The phrase reading tasks provide insight into the processing of natural language. However, in order to study the non-linearity of the Devanagari[43], a word reading task associated with different orthographic structures would be useful and has already been undertaken. Word reading studies with both early and late Hindi–English bilinguals would provide insight into the cortical reading networks of two different scripts and would clearly have implications for language-teaching methods in Indian schools. Clearly, many more studies are required to understand the processing of the Indian writing system and its similarities and differences with other writing systems of the world.

Appendix 1. Example stimuli

हवा और सूरज
बलवान कौन है
इतने में गरम
चोगा पहने एक
जो पहले मुसाफिर
वही ज्यादा बलवान

1. Perfetti, C. A., Liu, Y., Fiez, J., Nelson, J., Bolger, D. J. and Tan, L.-H., Reading in two writing systems: accommodation and assimilation of the brain reading network. *Bilingualism: Language and Cognition*, 2007, **10**, 131–146.
2. Paradis, M., Hagiwara, H. and Hildebrandt, N., *Neurolinguistic Aspects of the Japanese Writing System*, Academic Press, Orlando, 1985.
3. Lee, H.-S. *et al.*, Changes in brain activation patterns associated with learning of Korean words by Japanese: an fMRI study. *Neuroimage*, 2003, **20**, 1–11.
4. Tan, L.-H. *et al.*, Brain activation in the processing of Chinese characters and words: a functional MRI study. *Hum. Br. Mapp.*, 2000, **10**, 16–27.
5. Dong, Y. *et al.*, Essential role of the right superior parietal cortex in Japanese kana mirror reading. An fMRI study. *Brain*, 2000, **123**, 790–793.
6. Yoon, H. W., Cho, K., Chung, J. and Park, H., Neural mechanisms of Korean word reading: a functional magnetic resonance imaging study. *Neuro-Sci. Lett.*, 2005, **373**, 206–211.
7. Moore, C. J. and Price, C. J., Three distinct ventral occipitotemporal regions for reading and object naming. *Neuroimage*, 1999, **10**, 181–192.
8. Eden, G. F. and Zeffiro, T. A., In *Biopsychology* (ed. Jubilan B. M.), Guilford, Dushin/McGraw Hill, UK, 1998, pp. 192–196.
9. Price, C. J., The anatomy of language: contributions from functional neuroimaging. *J. Anatomy*, 2000, **197**, 335–359.
10. Horwitz, B., Rumsey, J. M. and Donohue, B. C., Functional connectivity of the angular gyrus in normal reading and dyslexia. *Proc. Natl. Acad. Sci. USA*, 1998, **95**, 8939–8944.
11. Tan, L. H., Liu, H.-L., Perfetti, C. A., Spinks, J. A., Fox, P. T. and Gao, J.-H., The neural system underlying Chinese logograph reading. *Neuroimage*, 2001, **13**, 836–846.
12. Liu, C.-L. *et al.*, Dissociated roles of the middle frontal gyri in the processing of Chinese characters. *Neuroreport*, 2006, **17**, 1397–1401.
13. Patel, P., In *Scripts and Literacy: Reading and Learning to Read Alphabets, Syllabaries, and Characters* (eds Taylor, I. and Olson, D.), Dordrecht, Kluwer Academic, Netherlands, 1995, pp. 265–276.
14. Bright, W., In *The World's Writing Systems* (eds Daniels, P. and Bright, W.), Oxford University Press, New York, 1996, pp. 384–390.
15. Vaid, J. and Gupta, A., Exploring word recognition in a semi-alphabetic script: the case of Devanagari. *Brain Lang.*, 2002, **81**, 679–690.
16. Karanth, P., The search for deep dyslexia in syllabic writing systems. *J. Neurolinguistics*, 2002, **15**, 143–155.
17. Oldfield, R. C., The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, 1971, **9**, 97–113.
18. Friston, K. J., Ashburner, J., Frith, C. D., Poline, J.-B., Heather, J. D. and Frackowiak, R. S., The spatial registration and normalization of images. *Hum. Br. Mapp.*, 1995, **2**, 165–189.
19. Talairach, J. and Tournoux, P., In *Co-planar Stereotaxic Atlas of the Human Brain*, Thieme, New York, 1988.
20. Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J.-B., Frith, C. D. and Frackowiak, R. S., Statistical parametric maps in functional imaging: a general linear approach. *Hum. Br. Mapp.*, 1995, **2**, 189–210.
21. Penny, W. D., Holmes, A. P. and Friston, K. J., In *Human Brain Function* (eds Frackowiak, R. S. J. *et al.*), Academic Press, Human Brain Function, 2003.
22. Brett, M., Christoff, K., Cusack, R. and Lancaster, J., Using the Talairach atlas with the MNI template. *Neuroimage*, 2001, **13**, S85.
23. Tarr, M. J. and Gauthier, I., FFA: a flexible fusiform area for subordinate-level visual processing automatized by expertise. *Nat. Neurosci.*, 2000, **3**, 764–769.
24. Dehaene, S., Clec'h, G.-L., Poline J.-B., LeBihan, D. and Cohen, L., The visual word form area: a prelexical representation of visual words in the fusiform gyrus. *Neuroreport*, 2002, **13**, 321–325.

25. Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S. and Dehaene, S., Language-specific tuning of visual cortex? Functional properties of the visual word form area. *Brain*, 2002, **125**, 1054–1069.
26. McCandliss, B. D., Cohen, L. and Dehaene, S., The visual word form area: expertise for reading in the fusiform gyrus. *Trends Cognit. Sci.*, 2003, **7**, 293–299.
27. Posner, M. I. and Petersen, M. E., The attention system of the human brain. *Annu. Rev.*, 1990, **13**, 25–42.
28. Chee, M. W. L., Weekes, B., Lee, K. M., Soon, C. S., Schreiber, A., Hoon, J. J. and Chee, M., Overlap and dissociation of semantic processing of Chinese characters, English words, and pictures: evidence from fMRI. *Neuroimage*, 2000, **12**, 392–403.
29. Lee, K.-M., Functional MRI comparison between reading ideographic and phonographic scripts of one language. *Brain Lang.*, 2004, **91**, 245–251.
30. Turkeltaub, P. E., Eden, G. F., Jones, K. M. and Zeffiro, T. A., Meta-analysis of the functional neuroanatomy of single-word reading: method and validation. *Neuroimage*, 2002, **16**, 765–780.
31. Fiez, J. A. and Petersen, S. E., Neuroimaging studies of word reading. *Proc. Natl. Acad. Sci. USA*, 1998, **95**, 914–921.
32. Sevostianov, A., Horwitz, B., Nechaev, V., Williams, R., Fromm, S. and Braun, A. R., fMRI study comparing names versus pictures of objects. *Hum. Br. Mapp.*, 2002, **16**, 168–175.
33. Fulbright, R. K. *et al.*, The cerebellum's role in reading: a functional MR imaging study. *Am. J. Neurorad.*, 1999, **20**, 1925–1930.
34. Smith, E. E., Jonides, J. and Koeppe, R. A., Dissociating verbal and spatial working memory using PET. *Cerebr. Cortex*, 1996, **6**, 11–20.
35. Wojciulik, E. and Kanwisher, N., The generality of parietal involvement in visual attention. *Neuron*, 1999, **23**, 747–764.
36. Marshuetz, C., Smith, E. E., Jonides, J., DeGutis, J. and Chenevert, T. L., Order information in working memory: fMRI evidence for parietal and prefrontal mechanisms. *J. Cognit. Neurosci.*, 2000, **12**, 130–144.
37. Bar, K. S., Gitelman, D. R., Parrish, T. B. and Mesulam, M.-M., Neuroanatomic overlap of working memory and spatial attention networks: a functional MRI comparison within subjects. *Neuroimage*, 1999, **10**, 695–704.
38. Sohn, M.-H., Ursu, S., Anderson, J. R., Stenger, V. A. and Carter, C. S., The role of prefrontal cortex and posterior parietal cortex in task switching. *Proc. Natl. Acad Sci. USA*, 2000, **97**, 13448–13453.
39. Ravizza, S. M., Delgado, M. R., Chein, J. M., Becker, J. T. and Fiez, J. A., Functional dissociations within the inferior parietal cortex in verbal working memory. *Neuroimage*, 2004, **22**, 562–573.
40. Fu, S., Chen, Y., Smith, S., Iversen, S. and Mathews, P. M., Effects of word form on brain processing of written Chinese. *Neuroimage*, 2002, **17**, 1538–1548.
41. Galletti, C., Kutz, D. F., Gamberini, M., Breveglieri, R. and Fattori, P., Role of the medial parieto-occipital cortex in the control of reaching and grasping movements. *Exp. Br. Res.* 2003, **153**, 158–170.
42. Dronkers, N. F., A new brain region for coordinating speech articulation. *Nature*, 1996, **384**, 159–161.
43. Kumar, U., Das, T., Bapi, R. S., Padakannaya, P., Joshi, R. M. and Singh, N. C., Reading different orthographies: an fMRI study of phrase reading in Hindi-English bilinguals. *Reading and Writing* 2009, doi: 10.1007/s11145-009-9176-8.

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