Neural representation of an alphasyllabary –
the story of Devanagari

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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, syllabic or logographic, 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. Korean, for example, is rather complex in that it is written in a mixture of three scripts: an alphabetic syllabary called hanguil, Chinese characters called hanja, and the Latin alphabet called romaja. Japanese is written in a mixture of four scripts: 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, Japanese, Korean and English 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, Korean and Japanese kana, 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. 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 syllabics 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. 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 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.

There have been no fMRI studies so far on the neural representations of alphabetic-syllabary 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.

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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 Ashokan inscriptions and has a Semitic source possibly dating as far back as the 5th century BC. 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. 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. 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. 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 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. 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. 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 into Talairach stereotactic space. 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. 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) for each participant were then taken into a second level analysis.

Group analysis was performed using the random effects approach 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 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. 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. In line with other studies on reading words and sentences, 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. 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. Meta-analyses of word reading studies 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

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

Coordinates of peak activation are reported for regions having at least 10 significant voxels.
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\textsuperscript{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\textsuperscript{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\textsuperscript{5}. 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\textsuperscript{35}, 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\textsuperscript{33}.

Activations of inferior parietal lobe (IPL) and insula were also observed. The role of dorsal IPL has been posited as part of a general attentional network\textsuperscript{36,35}. Additionally, it is also believed to be crucial for retaining temporal order information\textsuperscript{36}, attention switching\textsuperscript{37}, and task preparation\textsuperscript{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\textsuperscript{39}. Thus, VIPL is associated with a phonological encoding-recoding process (phonological short-term store) central to a variety of language tasks\textsuperscript{39}. Although the role of the inferior parietal region for word reading is still not clear\textsuperscript{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 and appears to play a significant role for visually guided motor tasks and disengaging attention from locations in visual space. 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. In Devanagari, for certain words, the vowel precedes the consonant in writing but follows it in speech. 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 temporoparietal, 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, 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 सुरज
बलवन वौँ है
इसने में गरम
चोगा पहनने एक
जो पहले मुझसम्बन्ध
वही व्यादि बलवत

RESEARCH ARTICLES


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