Reading Brainiacs
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Unlike learning to speak, learning to read and write requires years of explicit instruction. However, once a person learns to read well, reading is effortless, and in fact, obligatory. Skilled adult readers cannot refrain from reading, even if reading is impairing their performance. To demonstrate this, take the very simple Stroop test

In the lists below, try to name the ink color of each word out loud (so, for the first list you would say "red, green, blue..."

<table>
<thead>
<tr>
<th>List 1</th>
<th>List 2</th>
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<tbody>
<tr>
<td>Table</td>
<td>Computer</td>
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<tr>
<td>Chair</td>
<td>Sofa</td>
</tr>
<tr>
<td>Book</td>
<td>Plate</td>
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<tr>
<td>Paper</td>
<td>Mug</td>
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</tbody>
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Which list did you find easier? The first list was probably much easier than the second. That is because, even though the written words are completely irrelevant to the task, as skilled adult readers we cannot stop reading them. In the first list, the written words are simply random objects. However, in the second list, the written words are the incorrect colors, and they interfere with our production of the correct answer.

How do we go from struggling to read, sounding out one letter at a time, to becoming such skilled readers that we cannot even prevent ourselves from reading? And how does the brain change during the process of becoming a skilled reader? This article examines the neural mechanisms that underlie our ability to read. The beginning largely focuses on English, because the majority of scientific research on reading has been done with English. Later, the article covers the neural mechanisms behind reading other languages, including the akshara languages.

How We Read

Bottom-up processing

When we look at a word, many processes happen simultaneously below the level of conscious awareness. First, the feature detectors get activated. For example, when we see the letter 'T', the “horizontal line feature detector” and “vertical line feature detector” will get activated. These feature detectors will then activate the letter detectors that are consistent with them. For example, the “horizontal line feature detector” and “vertical line feature detector” might activate ‘F’ and ‘T’, but they will not activate ‘C’ or ‘S’. As more visual information about the stimulus is gathered, the letter detectors will settle on the correct letter, ‘T’. The letter detectors will then activate the word detectors that are consistent with them. For example, if you see the word “TAP”, the word detectors for “tap”, as well as similarly spelled words such as “cap”, “top”, and “tan”, will get activated. However, as more evidence is accumulated, the activity in the “tap” word detector will increase and suppress the activity in all the other word detectors. Eventually, the activity in the “tap” word detector will be so strong that we can identify the word.
When we read a word, all of the letters in that word start activating their letter detectors simultaneously (which is known as \textit{parallel processing}). Because of this, there is no length effect when we read; skilled adult readers can read 3 letter words and 7 letter words at approximately the same speed. This is in stark contrast to beginning readers who sound out words one letter at a time.

\textbf{Top-down processing}

The process I described above is purely \textit{bottom-up}, i.e., we process the simplest level (features) first, which go on to affect the next level (letters), which then affect the highest level (words). However, when we read, we use \textit{top-down} as well as \textit{bottom-up} information—our knowledge of words can influence how we perceive letters. For example, psychologists can briefly present letters on a screen (e.g., D or T) and ask participants to identify the letters. The presentation duration can be adjusted so that participants are only correct some of the time. Psychologists have found that if they present the same letters in the context of a word (e.g., HEAD or HEAT), performance actually improves! Note that in both cases, the same three letters are added in front of the critical letter (HEA), so they are not actually informative. However, what happens is that when “HEAD” is shown, the feature detectors activate the letter detectors, which activate the word detector for “HEAD”. Then the word detector sends positive feedback to the letters within it (H, E, A, and D). This feedback activation makes it easier to identify the letter ‘D’ when it is in the context of a word than when it is presented in isolation.

Here are a couple of other fun tasks. Can you identify what this says? I spilled some ink on it, but you may be able to make it out.

\textbf{READ}

Can you read these words?

\textbf{THE CAT}

And can you read this sentence? (pg. 47; Reprinted with the permission of Dr. Stanislas Dehaene)

\textit{Honey bees savour sweet nectar}

And how about these words?

\textbf{दत्तात्रेय प्रसन्न}

You probably thought the first item said “read”, the second item said “the cat”, the third item said “Honey bees savour sweet nectar”, and the fourth item said “\textit{दत्तात्रेय प्रसन्न}”. However, note that in the first image, the letter that is half-obscured by the spilled ink could either be an ’E’ or an ’F’. Furthermore, I never told you that the item was a word, all I said is “Can you identify what this says?” Therefore, both “READ”
and “RFAD” could be valid answers. But, you probably used your knowledge of words to influence your letter perception and didn’t even notice the ambiguity! In the second item, the letter ‘h’ and the letter ‘a’ are identical in visual form. However, you probably used your word knowledge while reading and perceived them as being different letters. In the sentence, did you notice that in the word “bees”, both e’s are actually c’s? In fact, in the word “nectar”, the ‘e’ and ‘c’ are actually both c’s as well! Therefore, in this sentence, the letter string ‘cc’ is repeated twice, and the first time we interpret it as ‘ee’ and the second time we interpret it as ‘ec’. Furthermore, in the word “savour”, the ‘a’ and the ‘o’ are the exact same shape! If you’re like most people, you were able to read that sentence with ease and didn’t even notice the misspellings.

In the Hindi words, did you notice that both ‘त्र’ and ‘न्न’ have the same visual form? However, your familiarity with that phrase likely influenced your akshara perception, causing you not to notice the ambiguity. That is because we use top-down information while reading; our world knowledge and spelling knowledge can influence our letter perception.

**Meaning and sound**

So far, we have been discussing identifying letters and words. However, reading is so much more than that; it is about linking the words to sounds and meanings. When we see a printed word, we can directly link it to its meaning, and then access its pronunciation. On the other hand, we can first link it to its pronunciation, and then access its meaning. Certain classes of words depend more heavily on one route than the other. For example, it is easier to directly access the meaning of a high frequency word (i.e., a word you encounter very often such as “the”). In contrast, for a low frequency word (such as “ebullient”), the link between the written form and the meaning may be weak, so it may be necessary to first access the sound of the word. For pronounceable non-words (such as “glorph”), it is possible to access their sound, but not their meaning (because they are meaningless). The direct access to meaning is more important for irregular words and homophones. For homophones, such as “waste” and “waist”, if you first accessed pronunciation and then the meaning, you would not be able to distinguish between the two. For irregular words (words with an irregular letter-to-sound correspondence such as “yacht”), it is difficult to go directly from the written form to the sound. Therefore, being able to directly access meaning is helpful.

Not only can word class influence how you read, but so can which language you are reading in. Orthographies vary in transparency, or how systematic the letter-sound correspondences are. Serbo-Croatian has a very transparent orthography, because every letter can only represent one sound and every sound can only be represented by one letter. English is moderately opaque; the letter ‘a’ represents different sounds in the words “cat” and “call” and the sound /f/ is represented by different letters in the words “fall”, “phone”, and “cough”. Hebrew and Arabic are even more opaque because the vowel sounds typically are not represented in the writing. Chinese is the most opaque orthography because the characters represent meaningful units, not sounds. Although portions of the characters (called phonetic radicals) can give a clue as to how the character is pronounced, one phonetic radical can have multiple pronunciations and the same sound can be represented using
multiple phonetic radicals. It is impossible to “sound out” a Chinese character. Orthographies which are more transparent rely more on first accessing the sound, and from that the meaning. In contrast, orthographies which are more opaque rely more heavily on first accessing the meaning, and from that, the sound.

The akshara languages are generally highly transparent. However, they do have one property that keeps them from being perfectly transparent: the inherent schwa vowel. In the akshara languages, the /uh/ vowel is not represented with a matra, it is said to be inherent. In Sanskrit, whenever the /uh/ sound was not supposed to be pronounced, this was marked with a halant. However, in many modern akshara languages, the /uh/ sound is typically not pronounced at syllable boundaries and at the ends of words, but this repression of the /uh/ sound is not marked with a halant. For example, in the Marathi word “प्रटकन” (which means quickly), there is an /uh/ sound after the ‘प’ and ‘क’. However, there is no /uh/ sound after the ‘न’ because it happens at a syllable boundary nor after the ‘न’ because it happens at the end of the word. Therefore, it is possible for the same akshara to be pronounced differently depending on the wider context. For example, the sequence ‘क’ is pronounced as /r.k/ (the period represents a syllable break) in the word “हरकन” but as /rak/ in the word “सरकना”. In general, the akshara languages can be read by linking each akshara to its corresponding sound to pronounce the word. However, some semantic knowledge is needed as well; you need some word knowledge to know when to pronounce the schwa vowel. Without this semantic information, people may mispronounce words. For example, when one child was trying to read the word “тhуkte” (stomping) in Bengali, he mispronounced it as /tхukate/.

Although orthographies vary in terms of their transparency, which affects how much people depend on sound while reading, all reading involves accessing sound to some extent. For example, which of the following words describes a type of flower? Answer as quickly as possible:

Tulip  Paper  Lamp  Hibiscus
Snow  Orchid  Violet  Lily
Daffodil  Internet  Daisy  Rows

Did you struggle a bit on the word “rows” because it sounds like “rose”? This is a perfect example of how people access sound while reading, even if the task does not require it. Studies of Chinese reading have also shown some homophone confusion. Therefore, there is some reliance on phonology even while reading a very opaque orthography.

There is also physiological evidence for the conversion of print to sound, even during silent reading. Researchers have found that people’s tongues move slightly even when they are reading silently. Furthermore, brain areas that are associated with speech production are activated by silent reading.

To summarize, there are two pathways that can be used while reading. In the first pathway, the words are first converted to sound, and then their meanings are accessed. In the second pathway, the meaning of a word is first accessed, and then
its pronunciation. Everyone uses both pathways to some extent, but the amount of reliance on a certain pathway can vary depending on word type or the orthography one is reading in. Studies of people with brain damage have provided more support for these separate pathways. For example, some patients have damage to the part of the brain that supports the conversion from print to sound. These patients have what is called deep dyslexia; they can still go from print directly to meaning but not from print sound. They often have trouble reading low frequency words that have very regular spellings, such as “sextant”. They also cannot sound out non-words, such as “glorph”. However, they have no problem reading high frequency words with irregular spellings such as “enough”. They might also make semantic errors while reading, for example if they see the word “ocean”, they might say “sea” 

In contrast, people with surface dyslexia have damage to brain areas that help convert print to meaning. They are able to read non-words and regular words such as “sextant”. However, they have a lot of trouble reading irregular words. For example, one patient read the word “enough” as “inog”.

What exactly are the brain structures that support the conversion from print to sound and from print to meaning? That question will be addressed in the next section.

A Closer Look at Brain Terms

The brain consists of four main sections, the frontal lobe (in the front), the temporal lobe (along the sides), the parietal lobe (on the top), and the occipital lobe (in the back).

Each lobule of the brain has sections in both the right and left sides of the brain. So, you can refer to “left temporal regions” or “right temporal regions”.

The brain has lots of folds. The valleys are known as sulci and the mountains are known as gyri.

The words used to describe directions in the brain are superior (closer to top of brain), inferior (closer to bottom of brain), anterior (closer to front of brain), posterior (closer to back of brain), medial (closer to middle of brain), and lateral (closer to outside of brain).

These terms will help you understand where certain brain structures are. For example, the “posterior superior temporal gyrus” refers to a mountain (gyrus) in the back, top part of the temporal lobe.
A Closer Look at Neuroimaging Techniques

**ERP:** In ERP, scientists place electrodes on a person’s scalp that can measure changes in electric potentials due to neuronal activity. This technique is known as electroencephalogram (EEG). These measurements of changes in electric potential are often very messy. So, scientists will average together multiple measurements to get smoother waves. These averaged wave forms are called ERPs (event-related potentials). For example, scientists may show people 100 words, 100 pseudowords, and 100 symbols. Then they will average together all the measurements from each category separately to get average wave forms. Then, they will compare the average wave form for the words, for the pseudowords, and for the symbols to see how word, pseudoword, and symbol processing is different in the brain. EEG is good at detecting when something occurs (i.e., it has good temporal resolution). It is not good at detecting where in the brain it occurs (i.e., it has poor spatial resolution).

![A person wearing an EEG net](image)

This graph shows time in ms on the x-axis and voltage on the y-axis. You can see that words, pseudowords, and symbols elicit different brain activity 170 ms after they are seen (the component is called the N170 because it is a negative going wave at 170 ms). This graph shows that words elicit the largest N170.

**MRI:** MRI stands for magnetic resonance imaging. To take an MRI, people lie in an MRI scanner, which uses powerful magnets to take pictures of people's brains. The settings on the MRI machine can be changed to take pictures of people's brain structures (structural scans) or to measure blood flow in the brain (functional scans, functional MRI = fMRI). During a structural scan, a person does nothing while lying in a scanner and the machine takes pictures of brain structures. During a functional scan, a person does a task in the scanner and the scanner measures changes in blood flow to different areas of the brain. Blood flow increases to areas that are needed to do the task. In this way, we can figure out what brain areas are used to do a task. fMRI is good for determining where in the brain something occurs (i.e., it has good spatial resolution) but is bad at determining when something occurs (i.e., it has poor temporal resolution).

![A picture of an MRI machine](image)
Brain Areas Used for Reading

Visual word form area

Each of the different processes we have discussed (identifying letters/words, accessing sound, and accessing meaning) is associated with a different brain area.

When we look at something (anything at all), this will immediately activate the brain’s lower level visual processing areas. These areas analyze the object’s most basic features (e.g., straight lines, curved lines, etc.). Then, depending on what object we are looking, this information will get sent to different high level visual areas. For example, the fusiform face area preferentially processes faces and the parahippocampal place area preferentially processes houses and landscapes. So, if we image a person’s brain when they are looking at pictures, all pictures will approximately equally activate the lower level visual areas. However, the fusiform face area will be more active for pictures of faces than of houses, whereas the opposite will be true for the parahippocampal place area.

This is a picture of a brain sliced in half so that you can see all the medial structures. The fusiform and parahippocampal areas labeled. The visual word form area is in the left fusiform gyrus whereas the fusiform face area is in the right fusiform gyrus.

The visual word form area is responsible for identifying words and letters. It is located in the left fusiform area and preferentially processes writing. It prefers scripts that you have learned (if a person can read Hindi, but not Kannada, his/her visual word form area would be more active when looking at Hindi words as compared to Kannada words).

If you were to image a person’s brain while they were looking at writing which was to the right of their center of gaze (i.e., in their right visual field), lower level visual areas in the left side of their brain would be activated. Similarly, if a person was looking at writing in their left visual field, lower level visual areas in the right side of the brain would be activated. In contrast, no matter which visual field a word is in, the visual word form area (which is in the left hemisphere) will get activated. Similarly, lower level visual areas distinguish between upper and lower case letters—‘A’ would activate neurons which process straight lines whereas ‘a’ would activate neurons which process curved lines. In contrast, the visual word form
area is case invariant; case does not affect its activity pattern. This was demonstrated using a clever repetition adaptation experiment. When a neuron is exposed to the same stimulus twice, it will be less active the second time. In the experiment, participants were shown either “HOTEL” followed by either “HOTEL” or “hotel”. In both cases, the activity in the visual word form area reduced by the same amount when the second word was presented. Therefore, the visual word form area is not simply responding to the visual features on the page, but is rather coding for abstract letter representations.

The visual word form area is not homogenous; different parts of it have slightly different roles. For example, say you were to show a person the words “anger” and “range”. These words are identical except for the position of the ‘r’. In fact, you can slightly shift their position on the page so that all of the letters, except for the ‘r’, line up. If you were to show a person the word “anger” followed by “range”, arranged so that the letters lined up, the posterior section of the visual word form area would show a repetition adaptation effect. However, this effect would not be seen if the letters were not lined up. In contrast, the area just one cm. in front of it would show a repetition adaptation effect even if the letters were not properly aligned. Therefore, the posterior section is position variant whereas the section in front of it is position invariant. In the most anterior section, no repetition adaptation effect would be seen because this region is not only sensitive to the letter identities, but also to the ordering of the letters.

1) anger
   RANGE
   The most posterior section of the visual word form area would show a repetition adaptation effect for #1, but not #2, because it is position variant (it needs the letters to line up). The section just one cm. in front of it would show a repetition adaptation effect to both #1 and #2 because it is position invariant. The most anterior section would not show a repetition adaptation effect in either case because it codes for the ordering of large chunks of letters.

2) anger
   RANGE
   The most posterior section of the visual word form area would show a repetition adaptation effect for #1, but not #2, because it is position variant (it needs the letters to line up). The section just one cm. in front of it would show a repetition adaptation effect to both #1 and #2 because it is position invariant. The most anterior section would not show a repetition adaptation effect in either case because it codes for the ordering of large chunks of letters.

It is known that readers of akshara languages also use the visual word form area while reading, but it is not known whether or not it is organized in the same way as it is in readers of English. The akshara languages and English are quite different; in akshara languages the vowels are typically represented by matras whereas in English they are represented by letters. This difference could affect the organization of the visual word form area. It is important to study basic reading processes in many different languages because not all phenomena work the same way in English and other languages.

When the visual word form area is damaged a very strange thing happens—patients have nearly perfect vision but they cannot recognize words! The first documented case of this was Mr. C in 1887. He had a small stroke that damaged some of the fiber tracts leading to the visual word form area. Although he had some other visual impairments, he could still recognize faces, name objects, and even read Arabic numerals! If he was shown a letter, his visual acuity was good enough to copy it, but he simply could not name it. Therefore, the problem was not visual, it was that there was a disconnect between the incoming visual information and the information about letters. However, the information about letters was not
completely lost; he could access it through his muscle memory. He was still able to write (although he could not read what he had written!) and recognize letters if he was allowed to trace over them with his fingers. His other language faculties: speaking, vocabulary knowledge, etc. were intact as well. This disorder is called pure alexia because only reading is severely impaired.

Another case of pure alexia was reported in 1981. This case was unique because the patient, Mr. N.R., could read both English and Kannada. When he first entered the hospital, he could only read by tracing over letters, similar to Mr. C. With therapy, he slowly regained his ability to read, although he never regained his reading speed. Interestingly, he found it easier to regain his English reading skill than his Kannada reading skill, even though he had learned Kannada first. This could be because of the visual properties of the two languages. English only has 26 letters, whereas Kannada has over 400 akshara. For example, in English, the letter 'k' is not affected by the letters that follow it. In contrast, in Kannada, the akshara क (/k/) can look different depending on which matras are attached to it.

Usually patients with pure alexia fall into two categories. Some patients cannot even recognize individual letters. Other patients can recognize individual letters, but not whole words. Therefore, they are able to read letter-by-letter, but their reading is very slow, especially for long words. Almost all of these patients either have damage to the visual word form area, to the connections going to it (so it cannot receive messages), or to the connections coming from it (so it cannot send message). Auditory areas

Once the visual word form area has analyzed the letters within a word, it sends the information to brain areas associated with sound and meaning. The brain areas that sound out written words are highly associated with the brain areas that process speech.

In one fMRI study, participants looked at letters, or listened to letter names, or did both simultaneously. Some visual areas in the occipital-temporal cortex were activated by written, but not spoken, letters. Auditory areas in the superior temporal cortex (including the planum temporale, Heschl’s gyrus, and middle part of the superior temporal gyrus) were activated by spoken, but not written, letters. The brain regions in between these two areas (superior temporal sulcus and posterior superior temporal gyrus) responded to both spoken and written letters. Therefore, these areas likely receive and integrate the information from the purely visual or auditory areas located nearby. Additionally, there were some areas in the anterior temporal cortex that only responded when both auditory and visual information was presented simultaneously. Interestingly, these brain areas were activated when the letters matched the sounds (e.g., the letter ‘o’ paired with the /oh/ sound) and not when they did not match (e.g., the letter ‘o’ paired with the /eee/ sound). This finding intrigued the researchers and they went on to see if there were any other areas that were more active to matching than non-matching stimuli. They found that some pure auditory areas (Heschl’s gyrus and the planum temporale) were more active to matching than non-matching stimuli. This is quite surprising because these are pure auditory areas; they do not process written letters. Therefore, if their activity increases when the visually and auditorily presented letters match, that
must mean that they are getting some input from the anterior temporal cortex, an area that processes both auditory and visual information\textsuperscript{3,21}.

This is a picture of the surface of the brain so that you can see lateral structures. The temporal lobe is highlighted in yellow. Some of the auditory structures (superior temporal gyrus and superior temporal sulcus) are labeled\textsuperscript{22}. Some of the semantic areas (middle temporal sulcus) are also labeled.

**Semantic areas**

When we are reading, we need to not only access the sound of a word, but also the meaning of the word. The region of the brain associated with accessing word meanings is the *middle temporal* cortex. This was demonstrated by a *repetition adaptation experiment*. In the experiment, participants were briefly shown one word; in fact the presentation of the word was so short that the participants were not even consciously aware of it. This word was followed by another for a longer period of time. Sometimes the second word was a synonym of the first (e.g., couch-sofa) and other times it was unrelated to the first word (e.g., couch-honey). The *left middle temporal* region was less activated by the synonyms, suggesting that it encodes the meanings of words\textsuperscript{3}.

Although the *left middle temporal* region is associated with accessing the meanings of words, it probably does not store the meaning but instead facilitates access of the meanings that are stored elsewhere in the brain. The *lateral temporal* region helps mediate the connection between word forms and their meanings. Different sections of the *lateral temporal cortex* specialize in different word classes. For example, the words “hammer”, “screw driver”, and “saw” would activate a distinctly different portion of the *lateral temporal* cortex than would the words “apple”, “orange”, and “banana”. In fact, people who suffer strokes can lose knowledge about a very specific category. Some patients lose all information about animals; they cannot recognize their pictures or answer simple questions such as “Where does a lion live?” However, their knowledge of other categories remains intact\textsuperscript{3}.
Verbs also activate the premotor cortex, the region of the brain that helps plan and guide movement. Furthermore, different verbs activate different sections of the premotor cortex. For example, words like “kiss” and “bite” activate the region of the premotor cortex that controls the mouth muscles whereas words like “walk” and “kick” activate the region of the premotor cortex that controls the leg muscles.

Pathways of reading
One clever study demonstrated how information travels between lower level visual areas, the visual word form area, phonological areas, and semantic areas. In the experiment, participants were shown 3 types of written stimuli: 1) high frequency, irregular words such as “have” or “eye”, 2) pseudohomophones: non-words that sound like real words (e.g., hed, wimen), or 3) pseudowords such as “trid” or “plosh”. Up till 150 ms, the brain activity for all three stimuli was identical and restricted to lower level visual areas. Immediately afterwards, the activity spread to the visual word form area. After that, the activity patterns for the three types of stimuli diverged. For pseudowords and pseudohomophones, the activity spread to the phonological areas in the superior temporal cortex such as the left planum temporale. For pseudowords, it stopped there. However, for pseudohomophones, the activity then spread to the semantic areas in the left middle temporal region. In contrast, for the low frequency, irregular words, the activity first went from the visual word form area to the semantic areas in the left middle temporal region. From there, it went on to activate phonological areas in the superior temporal region.

Timeline of Reading
The previous section focused on the “where”; it discussed fMRI studies that were able to identify the brain areas involved in reading. This section focuses on the “when”, fleshing out the time course of word identification. These studies primarily use ERP because it has good temporal (time) resolution.

ERP data look like a waveform. Different components of the wave are named based on when they occur and whether they are positive or negative. For example, the N170 is a negative-going wave that occurs 170 ms after seeing a word and the P100 is a positive-going wave that occurs 100 ms after seeing a word.
One of the earliest components associated with reading is the P100 and it is thought to be produced by the lower level visual areas. The next component is the N170. It is believed to be generated by the visual word form area and is associated with letter processing. It is hypothesized that the N170 is sensitive to bigram frequency, or how common the letter combinations within a word are. For example, the letter combination ‘th’ (such as in the word “that”) is very common. In contrast, the letter combination ‘gb’ (such as in the word “rugby”) is less common. Bigram frequency is a measure of how common all the pairwise letter combinations are within a word. It has been reported that words with large bigram frequencies elicit larger N170s than do words with low bigram frequencies.

Some effects of phonology are seen in the P200. For example, in one study, researchers showed participants words and non-words and had them decide whether or not they were real words. The words appeared in different colors, and sometimes the colors respected the syllable boundaries (e.g., blanket) whereas other times they did not (e.g., blanket). Words in which the colors were incongruent with the syllabic boundaries elicited larger P200s. Another study reported that low frequency, regular words elicited a larger P200 than low frequency, irregular words.

To study the processing of meaning, researchers showed participants sentences in which the final word did not make sense (e.g., “Dutch trains are sour”) or did make sense (e.g., “Dutch trains are yellow”). They found a wave that occurred 400 ms. after the last word was shown in which the wave was more negative if the last word did not make sense. This component is called the N400 and is associated with the processing of meaning. It is thought to be generated by temporal and prefrontal areas.

Therefore, within 1/10 of a second of seeing a word, the visual information travels from the eyes to the lower level visual areas of the brain. After another 1/10 of a second, the letters within the word begin to be processed by the visual word form area. After that, we begin to see evidence for sound and meaning retrieval.

Neural Differences Based on Writing System

So far, most of the work reviewed above is based on studies of alphabetic orthographies, specifically English. Research has shown that some of the brain areas identified by studies of English reading are also used when reading other orthographies. For example, the visual word form area has been shown to be used when reading Chinese, Japanese kana, Korean hangul, and Hindi. However, even within a family of orthographies, e.g., the alphabetic orthographies, some differences are seen depending on which language people are reading. For example, Italian is more transparent than English is. Studies have shown that readers of Italian use the phonological areas in the temporal lobe to a greater degree than do readers of English.

Even greater differences are seen when comparing readers of alphabetic and non-alphabetic orthographies. For example people reading phonologically-based orthographies such as English, Japanese kana, and Korean hangul rely on different brain areas than people reading morphosyllabic orthographies, such as Chinese, Japanese kanji, and Korean hanja. A few studies had people who speak both Chinese and English lay in an fMRI scanner while they read words in both languages. They
found that when people read English, they mainly rely on the left occipito-temporal region (which includes the visual word form area). In contrast, when people read Chinese, they use occipito-temporal region in both the left and right sides of the brain. Furthermore, readers of English use the left inferior frontal cortex, a brain region associated with phonological processing. In contrast, readers of Chinese use the left middle frontal gyrus. Although the function of the left middle frontal gyrus is not entirely clear, it is believed to be associated with the access of specific character forms. Because Chinese cannot be “sounded out” like English words can, each individual character must be recalled. The left middle frontal gyrus may be associated with accessing these individual character representations.²⁶

A Closer Look at Writing Systems

Writing systems are named after the unit of sound they represent.

**Alphabets:** In alphabets, each letter represents a phoneme, the smallest unit of sound. For example, in the word “cat”, the letter ‘c’ represents the /k/ sound, the letter ‘a’ represents the /aaah/ sound, and the letter ‘t’ represents the /t/ sound. Examples of alphabets are English, French, Spanish, Russian, Greek, and Korean hangul.

**Alphasyllabaries:** In alphasyllabaries, each graph represents a syllable but subcomponents of the graphs represent phonemes. Vowels are typically attached to consonants using matras. Examples of alphasyllabaries include Hindi, Thai, and Kannada. Note that रे and रे share one component, रे.

**Syllabaries:** In syllabaries, each graph represents a syllable that cannot be subdivided into phonemes. Japanese kana is an example of a syllabary. Note that れ (/re/) and ろ (/ro/) look nothing alike.

**Morphosyllabaries:** In morphosyllabaries, each character represents a unit of meaning. Many characters have two components, semantic and phonetic radicals. The semantic radical cues the meaning of the whole character and the phonetic radical cues the pronunciation of the whole character. Chinese, Japanese kanji, and Korean hanja are examples of morphosyllabaries.

This is a picture of the brain surface. The highlighted portion shows the middle frontal gyrus and the inferior frontal sulcus.⁴⁹
**Chinese:** Like I mentioned above, most Chinese characters have two components, a semantic and phonetic radical.

This is the character that means mother and is pronounced /ma/. Its semantic radical means female and cues the whole character’s meaning. Its phonetic radical is pronounced /ma/ and cues the whole character’s pronunciation.

**Japanese:** Japanese uses multiple orthographies, a syllabary called kana and Chinese characters called kanji. Kana is typically used for grammatical functions and foreign words. Kanji is typically used for content words, such as nouns and verbs. Both orthographies are used together within the same text.

**Korean:** Korean also uses multiple orthographies, an alphabet called hangul and Chinese characters called hanja. In hangul, each letter represents a phoneme. However, rather than use a linear organization like most alphabets, in hangul the letters are organized into syllabic blocks.

The word “hangul” written in hangul. Note that the first syllable, /han/ forms one block and the second syllable /gul/ forms the second block.

**South and Southeast Asian:** Most South and Southeast Asian orthographies are alphasyllabaries. They tend to have the following features:

1) **Transparent:** Most akshara have only one pronunciation.

2) **Inherent Vowel:** The schwa vowel (makes the /uh/ sound) is said to be inherent in every consonant; it typically is not orthographically represented in the middle and ends of words.

3) **Visually complex:** Akshara represent syllables and are composed of phonemic subcomponents. Because of this, most South Asian orthographies have over 400 akshara. Furthermore, each individual akshara tends to be visually complex. For example, consider how many more lines there are in the akshara “ना” than in the letter ‘b’. One study looking at Kannada reading acquisition found that children learn visually simple akshara faster than more visually complex akshara.

4) **Non-linear:** Although the orthographies are generally read from left to right, each individual akshara can be non-linear. For example, in “क़ि” the /क/ is written before the /ि/ but pronounced after the /ि/.
Another study also compared alphabets and morphosyllabaries, but rather than compare English and Chinese, it compared Japanese kana and kanji. Japanese kana represents the sounds of language. Japanese kanji is based on Chinese characters and every character represents meaning. In this study, participants had to lie in an fMRI scanner while reading kana and kanji words. Kanji words activated the right fusiform gyrus to a greater degree than kana did. These results dovetail nicely with the English-Chinese results described above. Japanese kana activated the left inferior parietal area (which includes the supramarginal gyrus, an area associated with phonological processing) to a greater degree.

Korean is similar to Japanese in that it can be written in two orthographies: Korean hangul and Korean hanja. Korean hangul is an alphabet, and every letter represents a sound. Korean hanja is based on Chinese characters, and every character represents meaning. Therefore, it is possible to write the same Korean word using either hangul or hanja. They will both have the same pronunciation and meaning, but they will be written very differently. In the study, participants had to lie in an fMRI scanner while reading words in either hangul or hanja. The researchers found more activation in the right middle occipital gyrus and right fusiform gyrus when participants were reading hanja as compared to hangul. They also found that the angular and supramarginal gyri (areas associated with phonological processing) were more active when reading hangul as compared to hanja. Both of these findings are very similar to the Japanese findings presented above.

Although Korean hangul is alphabetic, it is different from other alphabets in that the letters are arranged into syllabic blocks. One neuroimaging study of Korean found that Korean hangul generally activates the same brain areas that other alphabetic orthographies do. However, there were a few significant differences. For example, Korean reading activated right occipito-temporal regions to a greater degree than other alphabets did. Furthermore, Korean activated the posterior portion of the right dorsolateral prefrontal cortex. It is possible that these areas are
recruited because Korean is more visually complex than other alphabets and uses a non-linear arrangement of letters 30.

Hindi and Korean hangul are similar in that they both represent the sounds of language at both the syllabic and phonemic level. Akshara represent syllables, but subcomponents of the akshara, such as matras, represent phonemes. In Korean hangul, the letters represent phonemes but they are arranged in syllabic blocks. Hindi and Korean also both have a non-linear spatial arrangement. Furthermore, Hindi and Korean tend to be transparent.

One study comparing English and Hindi had participants lie in an fMRI scanner while they read English words and linear Hindi words (e.g., कम). The researchers found that Hindi reading used phonological areas such as the left inferior parietal lobule whereas English reading used semantic areas such as the left inferior temporal gyrus. This is likely because Hindi is more transparent than English 31.

Another study comparing English and Hindi had participants lie in an fMRI scanner while they read short phrases in both Hindi and English. Unlike in the previous study, in this study some of the Hindi words were non-linear. Hindi activated the right caudate nucleus to a greater degree, likely because Hindi is more visually complex than English 32.

Another study of Hindi reading was able to study Hindi’s non-linear nature in more detail. In this study, people lay in an fMRI scanner while reading either linear words such as “फल” or non-linear words such as “किरण”. When people read non-linear words, there was more activation in right temporal areas and the cerebellum 33.
What Changes Does Learning to Read Precipitate?

Reading changes the way you hear language

Did you know that reading can fundamentally change both how you hear language and the structure of your brain? To demonstrate that, try doing this simple task: tell me what sounds you hear in the word “coat”. You probably heard /k/, /o/, and /t/ right? Fairly simple? Although it seems easy, it seems that people can only do this task if they have learned to read an orthography that code for phonemes. Illiterates (people who grow up in societies where literacy is uncommon, not people who are unable/unwilling to learn to read) find this task very difficult, as do adults who only know how to read Chinese characters. Children quickly learn to do this after they begin learning to read.

The above task tested your phonemic awareness, or your conscious awareness for phonemes (the smallest unit of sound) in spoken language. In contrast to phonemic awareness, people seem to have syllabic awareness even without literacy education; young children can tell you that the word “computer” has three syllables even before they learn to read.

Although learning to read increases your phonemic awareness, the precise spellings of words can trip people up. For example, how many sounds do you hear in the word “judge”? If you said three, you are correct! The three sounds are /j/, /uh/, and /j/. However, many people get confused and say that the word has four sounds because they “perceive” the silent ‘d’. Similarly, how many sounds do you hear in the word “pitch”? How about the word “rich”? They both have the same number of sounds (3), but people will accidentally say that “pitch” has four sounds because they “perceive” the silent ‘t’.

We know that learning to read an alphabet increases phonemic awareness because the letters represent phonemes. In contrast, learning to read Chinese does not increase phonemic awareness because the writing system does not represent the sounds of language. So, one remaining question is, does learning to read an alphasyllabary increase phonemic awareness? Akshara represent syllables, not phonemes. However, akshara subcomponents do represent phonemes, so it is possible that learning to read an alphasyllabary does increase phonemic awareness. The evidence suggests that learning to read an alphasyllabary increases phonemic awareness to a limited extent. One study compared illiterate and monoliterate Hindi speakers (can only speak and read Hindi) on some phonemic awareness tasks. On the phoneme oddity task, they heard four non-words. Three of the non-words contained the same phoneme, whereas one of them did not. They had to identify the one that did not fit with the rest (e.g., Which of these words do not have the sound /p/ in it: परा, पुष्प, नसो, पोटे?). In the phoneme deletion task, they heard a word and were asked to remove one phoneme from it (e.g., Q: What is “पाली” without the /y/ sound? A: “पाली”). The monoliterates were 92% accurate on the phoneme oddity task.
whereas the illiterates were only 32% accurate. Similarly, the monoliterates were 46% accurate on the phoneme deletion task, whereas the illiterates were only 8% accurate. Clearly, the monoliterates did better than the illiterates, so learning to read an alphasyllabary does promote phonemic awareness. However, the monoliterates did much worse than a group of biliterates (people who can speak/read both Kannada and English). That group was 99% accurate on the phoneme deletion task (remember the monoliterates were only 46% accurate). Therefore, it seems that learning to read an alphasyllabary promotes phonemic awareness to a limited extent, but not as much as learning to read an alphabet.

Phonemic awareness also develops more slowly in readers of alphasyllabaries as compared to readers of alphabets. For example, English-speaking children around the age of 5.6 years are 30-50% accurate on phoneme deletion tasks and nearly perfect by 9.5 years. However, Kannada-speaking children do much worse on a task very similar to the phoneme deletion task, called a phoneme substitution task. In the task, they are asked to replace one phoneme with another one (e.g., Q: Can you substitute the /a/ sound in the word “loka” with the /e/ sound? A: “loke”). On the phoneme-substitution task, 6 year old Kannada-speaking children were 5-8% accurate and 9.5 year olds were 51-58% accurate. Therefore, it is clear that phonemic awareness emerges much more slowly in Kannada speaking populations than in English speaking ones.

Similar to how English spellings can trip people up, so can spellings in alphasyllabaries. For example, in the study comparing monoliterate and illiterate Hindi speakers described above, 95% of the monoliterates could delete the /ṛ/ sound from “रेली”, since the /ṛ/ is represented by a matra. In contrast, participants found it difficult to delete the /न/ from “नवी”, because the schwa is inherent and not represented with a matra. Although the correct answer is /अवी/, the most common answer was /वी/. Similarly, approximately 90% of the literate participants could delete the /व/ sound from “व्याली”, since it is easy to see the parts of that consonant cluster which represent the /p/ and /y/ sounds respectively (प + व = व्य). However, only 35% of them could delete the /र/ sound from the word “प्रका”, because it is hard to distinguish the distinct parts in that consonant cluster (प + र = प्र). Another study done with biliterate Marathi-English speakers found that although they generally had good phonemic awareness, they specifically struggled with the schwa vowel in Marathi. In the study, participants were asked to state which sounds they heard in some Marathi and English words (e.g., Q: What sounds do hear in the word “dirtily”? A: d-uhh-r-t-i-l-eee; Q: What sounds do you hear in the word “ख्वाजा”? A: d-uhh-r-v-a-z-a). Note that the structure of both words is identical, consonant-schwa vowel-consonant-consonant-vowel-consonant-vowel. In general, people tended to get the English word correct, whereas they missed the schwa vowel in the Marathi word. This is because English represents the schwa vowel with the letter ‘i’ in this case, whereas in Marathi the schwa vowel is not represented in the written form. Remember that the people were not shown the spellings; this task was done completely orally. However, people remembered the spellings in their heads while doing the task, so the differences in writing system were able to affect their performance.
**Reading changes the brain**

Reading not only changes how we hear language, but it also changes the structure and function of the brain. One study compared the brain structure of illiterate adults and ex-illiterates (adults who had recently learned how to read). All the adults lived in Columbia and were matched on factors such as socioeconomic status. The researchers found that the adults who had recently learned how to read had more *gray matter* in higher-level visual processing areas in the occipital cortex as well as areas associated with *phonological* and *semantic* processing such as the left supramarginal gyrus, superior temporal cortex, angular gyri, and posterior *middle temporal* regions. They also had more *white matter* connecting the angular gyri on both sides of the brain 40.

![Brain Diagram](image)

*This picture of the surface of the brain shows lateral structures. The angular gyrus is highlighted in yellow. The supramarginal gyrus (labeled) is to the left of the angular gyrus. The superior and middle temporal regions are also labeled.* 28

Another study compared illiterate, ex-illiterate, and literate (learned to read in childhood) adults living in Portugal and Brazil. However, instead of using *structural scans* like the previous study did, they used *functional scans*. In the study, the researchers had participants listen to speech while they measured activation levels in the brain. They found that when literate and ex-illiterate participants listened to sentences they had more activation in *phonological* areas such as the *planum temporale* than did illiterates. When literates and ex-literate listened to words and were asked to decide whether or not they were real Portuguese words, they had more activation in the *visual word form area* than did illiterates. The fact that the words were only presented orally but the literates and ex-literates were recruiting the *visual word form area* suggests that they are thinking about the spelling of the word when making their decision. Both of these findings provide neural support for the previous section, that literacy changes how we hear spoken language 41.

The same study also showed participants images of things like words, tools, houses, faces, and checkerboard patterns. They found that illiterates had the lowest level of activation in visual areas in the occipital cortex when looking at pictures, suggesting that literacy enhances visual processing. Activity in the *visual word form*
area was lowest in illiterates when looking at words, suggesting that literacy enhances its responsivity to words. Furthermore, illiterates had more activity in the visual word form area when looking at faces than did the literates and ex-literates. This finding is very interesting and requires a bit more explanation. Reading is a rather recent cultural innovation, so our brains did not evolve for reading. Therefore, it is highly unlikely that we have brain areas devoted to reading. Rather, reading likely took over brain areas that were meant other purposes. Therefore, the fact that faces strongly active the visual word form area in the brains of illiterates suggests that both the left and right fusiform gyrus were originally face processing areas. In literates, words pushed faces out of the left fusiform area, so faces are mainly processed by the right fusiform. However, in illiterates, faces continue to be processed by both the left and right fusiform. This raises the intriguing possibility that illiterates may have better facial recognition than literates. Scientists are currently working to see whether or not that is true 41.

**Summary**

Although reading processes areas slightly different across languages, learning to read is essentially learning to link print to both sound and meaning. People employ both bottom-up and top-down processes to successfully do so. Learning to read also fundamentally changes brain structure and the brain's response to visual and auditory stimuli. Although learning to read is challenging, once people become skilled readers, they read words automatically.

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**Glossary of Terms**

*Bigram Frequency*- How common the pairwise letter combinations within a word are

*Bottom-up/top-down processing*- Bottom-up processing is when words are read by focusing on the printed features. Top-down processing is when words are read using word knowledge and world knowledge.

*Case Invariant*- The brain's response is the same whether the word is written in uppercase or lowercase letters. This is the opposite of case variant.

*Deep/Surface Dyslexia*- People with deep dyslexia have damage to brain areas that connect print to sound. They have trouble reading low frequency words and sounding out non-words. They often make semantic errors while reading (e.g., when they see “ocean”, they say “sea”). People with surface dyslexia have damage to brain areas that connect print to meaning. They have trouble reading irregular words.

*Functional scans (fMRI = functional magnetic resonance imaging)*- People lay in an MRI scanner for this type of scan. However, the settings on the machine are changed so that rather than taking pictures of brain structures, the brain is able to measure blood flow. Parts of the brain that are more active during a particular task will
require more blood. By detecting changes in blood flow, scientists can figure out which brain structures are used for different tasks.

**Fusiform Face Area** - This area of the brain preferentially processes faces. It is in the right fusiform gyrus. It occupies the same space in the right hemisphere that the visual word form area occupies in the left hemisphere.

**Gray Matter** - Neurons have 3 parts, dendrites which receive information from other neurons, cell bodies where basic cellular processes are carried out, and axons which carry information to other neurons. The gray matter is the part of the brain that mainly contains cell bodies.

**High Frequency word** - A word that you encounter very frequently (e.g., the)

**Homophone** - Two different words that are pronounced the same (e.g., waste, waist)

**Irregular** - A word whose spelling-sound correspondence doesn’t match the rules of the language (e.g., yacht, pint, colonel, enough)

**Lateral Temporal Area** - Helps mediate the connection between word forms and their meanings. Different sections of the lateral temporal cortex specialize in different word classes (e.g., animals, tools, fruit, etc.)

**Low Frequency word** - A word that you don't encounter frequently (e.g., ebullient)

**Middle Temporal Area** - An area of the brain that facilitates access of the meanings that are stored elsewhere in the brain

**Orthography** - The way a writing system is implemented in a particular language. It is possible for the same language to have more than one orthography, for example Japanese can be written in either kana or kanji and Korean can be written in either hangul or hanja.

**Parahippocampal Place Area** - This area of the brain preferentially processes places (e.g., houses).

**Parallel processing** - All of letters are processed at once, as opposed to sequentially. Due to parallel processing, words of different lengths can be read equally quickly.

**Phoneme** - The smallest unit of sound

**Phonemic Awareness** - Conscious awareness of the phonemes in spoken language. This typically develops after learning to read an orthography that represents phonemes.

**Phoneme Deletion Task** - A task in which a participant hears a word and is asked to repeat the word without one phoneme (e.g., Q: What is “प्याली” without the /y/ sound? A: “प्याली”).

**Phoneme Oddity Task** - A task in which a participant hears a series of words. All of the words except one will share a phoneme. The participant has to choose the word that does not have the target phoneme (e.g., Which of these words does not have the sound /p/ in it: पत्र, पूरी, नसों, पटे?).

**Phoneme Substitution Task** - A task in which a participant is asked to replace one phoneme with another one (e.g., Q: Can you substitute the /a/ sound in the word “loka” with the /e/ sound? A: “loke”).

**Phonological** - Refers to sound

**Planum Temporal** - An area of the brain that processes sound.

**Position Invariant** - The brain area is not sensitive to where the letters are in the visual field. This is in contrast to brain areas that are position variant.

**Premotor Cortex** - The area of the brain that helps plan and guide movement.
**Pure Alexia**- This is caused by damage to the visual word form area, connections leading to the visual word form area, or connections coming from the visual word form area. Patient with pure alexia have a lot of trouble reading words, but their other faculties are unaffected.

**Regular**- A word whose spelling-sound correspondence matches the rules of that orthography (e.g., cat, mint, sextant)

**Repetition Adaptation**- The brain has a smaller response when it is exposed to the same stimulus twice in a row. If the brain’s response gets smaller when it is exposed to two different stimuli that means that it is treating the two stimuli as equivalent.

**Schwa Vowel**- The vowel that makes the /uuhhh/ sound. It is typically not orthographically represented in akshara languages.

**Semantic**- Refers to meaning

**Stroop test**- A test in which people are asked to name the ink colors of words. People are faster when the words are random objects than when they are color names that do not match the ink colors.

**Structural scans (MRI = magnetic resonance imaging)** - People lay in an MRI machine and it takes pictures of their brain structure. These can be used to look at the size of different brain structures and get measurements on the density of gray and white matter in different areas.

**Syllabic Awareness**- Conscious awareness of the syllables in spoken language. This typically develops without literacy education.

**Transparency**- How systematically letters map onto sounds in a language. In transparent orthographies, each letter has only one pronunciation and each sound corresponds with only one letter. In opaque orthographies, one letter can correspond with multiple sounds and one sound can be represented by multiple letters.

**Visual Field**- Anything to the right of your center of gaze is in your right visual field. Anything to the left of your center of gaze is in your left visual field. Information from the right visual field gets sent to lower level visual processing areas in the left side of the brain and vice versa.

**Visual Word Form Area**- This area of the brain preferentially processes written words. It is in the left fusiform gyrus.

**White Matter**- Axons form long tracts that carry information from one brain area to another. These axonal tracts are known as white matter.

**Works Cited**