The Eye-tracking Method and its Application in Language Research
Day 2: Reading

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1 Basic patterns

Someone with no knowledge of eye movements may have the impression that during reading, the eye sweeps across the text continuously; this impression is of course an illusion. Like in unconstrained scene-viewing, eye movements in reading consist of a series of fixations and saccades.

- On average, a fixation during reading lasts 200-250ms.
- With each saccade during reading, the eye gaze usually moves about 7 to 9 letters for readers of English.
- During reading, about 10-15% of saccades go backwards (*regressive saccades*).
- *Return sweeps* refers to the eye movement from the end of one line to the beginning of the next. They usually start from 5-7 letters before the end of a line to 3-7 letters after the beginning of the next line.
- There are considerable individual differences in terms of average fixation duration and saccade length in reading.

You may have noticed that saccade length is measured in letter spaces rather than viewing angles in reading. This is because saccade length during reading is relatively unaffected by the retinal size of the text: the eye moves about 7-9 letters with each saccade regardless of whether the text is 36cm to the eye or 72cm (or size 36 vs. 72).

Eye movements are not exactly the same across different writing systems. For example, readers of Chinese (where a character corresponds to a morpheme) typically move their eyes about 2 characters with a saccade; and readers of Japanese (where a character corresponds to a morpheme (*kanji*) or a syllable (*kana*)) have an average saccade length of 3.5 characters. In Hebrew, where vowels are often not represented orthographically, the average saccade length is also shorter than in English (5.5 characters/letters vs. 7-9 letters). The difference in saccade length across languages can be attributed to the difference in information density: while a word is on average 5 letters in English, it is about 2 characters in Chinese and Japanese. When the number of words is considered rather than the number of letters/characters, the average saccade lengths in English, Chinese, Japanese, and Hebrew are roughly comparable [1].

2 Sources of information during reading

The fovea is where visual acuity is the highest and vision the sharpest, but it is not the only region on the retina where information can be obtained. During scene perception, it has been shown that information of all levels can be processed parafoveally (i.e. information can be obtained from the parafovea, the region that circumscribes the fovea), from low-level features such as colour and orientation to high-level information such as semantic meaning (the gist of a scene).

2.1 Perceptual span in reading

Perceptual span refers to the area from which readers can obtain useful information. An abundance of studies have investigated the size of perceptual span during reading, mainly using the moving window/moving mask paradigm. The perceptual span is asymmetrical around the centre of fixation. In English, the perceptual span
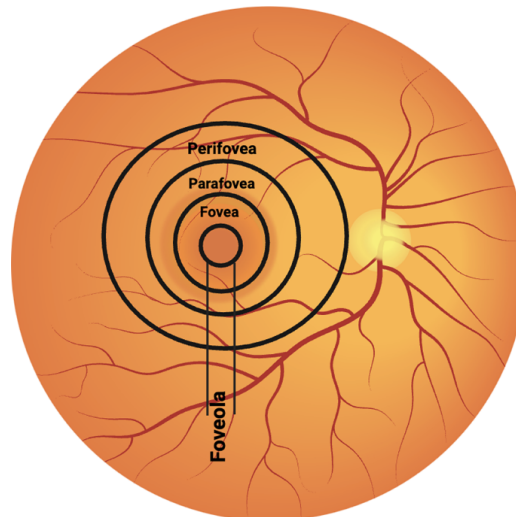
Figure 1: Photograph of the retina of the human eye, with overlay diagrams showing the positions and sizes of the macula, fovea, and optic disc. Extract from [2].

during reading is about 3 to 4 letters to the left of the current fixation and 14 to 15 letters to the right, i.e. from the beginning of the current word to 2 words to the right. In languages written right-to-left, the perceptual span is reversed [1].

Foveal vs. parafoveal vision within the perceptual span Results from moving mask experiments have shown that foveal processing is vital in reading while parafoveal processing is beneficial but also has limitations. When the moving mask is small enough to allow some letters into the fovea, participants read at a reduced rate but can still obtain information. As the size of the mask increases, reading efficiency drops rapidly. When the mask covers the entire fovea but only some of the parafovea, readers make large numbers of errors when reporting the sentence.

While parafoveal vision has many limitations, the boundary paradigm has shown that quite a few types of information can be processed parafoveally during reading. Preview benefits can be obtained from previews that overlap with the target word in terms of orthography [3], phonology [4], as well as morphology (especially in languages such as Chinese where morphological structure plays a more important role in word recognition)[5].
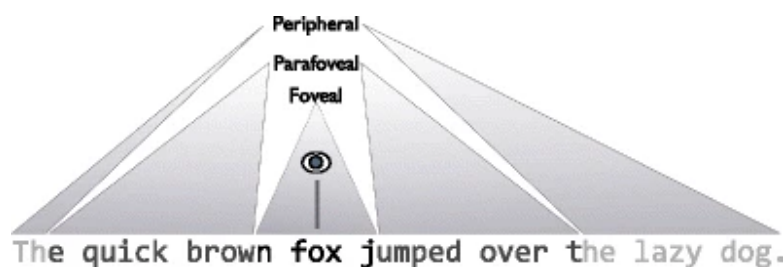

Figure 2: The foveal, parafoveal, and peripheral regions when three characters make up 1° of visual angle. The eye icon and dotted line represent the location of fixation. Extract from [6].

2.2 Experimental paradigms

A type of experimental paradigm that has been very successful in investigating foveal vs. parafoveal vision in reading is called the gaze-contingency paradigm, in which the visual display changes depending on where the reader is looking. Here are some main types of this paradigm.

Moving window/moving mask paradigms How do foveal and parafoveal visions contribute to reading? A clever way to investigate this is to dissociate these two types of vision in the laboratory. In the moving window paradigm, valid information is only provided within a window area around the gaze location, with the

text outside the window replaced by other letters. Conversely, in the moving mask paradigm, foveal letters are masked while only letters in the parafovea and the periphery are retained.

Moving window paradigm

```
This is a xxxxxxxx xxx xxxxxxxxxxxxx xxxxxxxx.
  *

xxxx xs a sentence fox xxxxxxxxxxxxx xxxxxxxx.
            *

xxxx xx x xxxtence for demonxxxxxxxx xxxxxxxx.
                  *

xxxx xx x xxxxxxxx xor demonstratiox xxxxxxxx.
                          *

xxxx xx x xxxxxxxx xxx xxxxxxxxxtion purposes.
                                    *
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Figure 3: The moving window paradigm. Extract from [7].

```
It is well known XXXXXXXewers can allocate attention independent
                      +

It is well known thatXXXXXXXs can allocate attention independent
                        +

It is well known that viewersXXXXXXXlocate attention independent
                          +
```

Figure 4: The moving mask paradigm. Extract from [8].

Boundary paradigm In the boundary paradigm, a target word is replaced by a preview word while the reader fixates on the prior parts of the text. When the reader's eye passes an invisible boundary, the preview changes to the target. If the target is processed faster (i.e. shorter fixation times) when the preview is related compared with when it was unrelated, there has been a preview benefit.

```
It is well known that hbgkrsk can allocate attention independent
                          +

It is well known that viewers can allocate attention independent
                          +
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Figure 5: The boundary paradigm. Extract from [9].

3   Reading eye movement measures

Common measures you may see in a reading eye-tracking experiment[1]:

On the word level:

- **First-fixation** duration: the duration of the first fixation on a word.
- **Single-fixation** duration: those cases where only a single fixation is made on a word.
- **Gaze duration**: the sum of all fixations on a word prior to moving to another word.
- **Probability of skipping**: the probability that the reader does not fixate on a word/region when moving from left to right across a text (if language is written left-to-right).

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[1]Although some try to link these different measures with distinct cognitive processing; e.g. some researchers argue that first fixation duration reflects earlier-occurring processes (i.e., word recognition), and gaze duration reflects later-occurring processes (i.e., integration), it is not possible to fully distinguish the different processes with these measures [10]. You should pay attention to what the researchers are reporting as well as how they interpret it when reading a paper.

On the sentence / region of interest (ROI) level:

- **First-pass** duration: the amount of time from when a reader first fixates on a region to when they first leave that region.
- **Go-past** duration/**Regression path** duration: the amount of time from when a reader first fixates on a region to when they first leave that region to the right (if language is written left-to-right).
- **Second-pass** duration: the sum of all refixations on a region of text after the eye has already moved past that region in the text.
- **Total duration**: the sum of initial processing of a target region (i.e., first-pass duration) and any subsequent rereading of that region (i.e., second-pass duration).

4   Eye movements and language processing: Word recognition

Research has shown that reading time on the word level is influenced by a variety of factors, including word frequency, word familiarity, age of acquisition, lexical ambiguity, and contextual plausibility. These factors are believed to impact the process of word recognition (as opposed to later processes such as interpretation or integration), as reflected in early eye movement measures such as first fixation, single fixation, and gaze duration.

Word Frequency and Length   One of the most well-documented factors affecting reading time is **word frequency**: the more frequent a word is, the less time readers spend processing it [11]. However, word frequency is often confounded with **word length** in natural language, since longer words tend to appear less frequently. Even when controlling for word length, word frequency continues to significantly impact reading time. For example, Rayner's research indicates that the size of the frequency effect is 20–40 ms in first fixation duration and 30–90 ms in gaze duration [12,13].

Interestingly, the frequency effect diminishes with repetition: after a word is encountered a few times in a passage, the difference in reading time between frequent and infrequent words becomes negligible by the third instance [14].

Word Familiarity and Age of Acquisition   Independently, **word familiarity** has been shown to have an impact on reading times, as well, with readers spending less time on more familiar words [15,16]. In addition, **age-of-acquisition** can affect how long it takes to process a word, and thus has an effect on reading times, as shown by Juhasz and Rayner [17,18].

Lexical Ambiguity   The presence of **lexical ambiguity**—when a word has multiple meanings—can further influence reading times. Words that are balanced in ambiguity (i.e., where multiple meanings are equally likely, for example *coach*) tend to be read more slowly than unambiguous words or biased ambiguous words (those with a clear dominant meaning, for example *bark*) [19].

Morpheme frequency   There is evidence that readers decompose words into their constituent morphemes while reading. Research shows that the **frequency of individual morphemes** affects reading times independently of overall word frequency [20–22]. This effect occurs not only with transparent compound words (e.g., punishment = punish+ment), but also with opaque compounds (e.g., casualty ≠ casual+ty), suggesting that readers may routinely decompose compound words, even when it doesn't aid in lexical processing [20].

Contextual constraint   Finally, the time spent reading a word is also influenced by the **context** in which it appears. A substantial body of research has demonstrated that words which are predictable from the preceding context are read more quickly than less predictable words [e.g., 23,24,25]. However, some researchers argue that this reduction in reading time may not necessarily reflect differences in the word recognition process itself. Instead, it may be due to *post-lexical* processes, such as integrating the word's meaning into the broader context of the sentence [26].

5   Eye movements and language processing: Sentence processing

To fully comprehend a text, word recognition is just the initial stage. The reader must also process the grammatical structure of each sentence, identifying how each word fits into this structure—a process known as syntactic parsing. Additionally, the reader must integrate the meanings of individual words and phrases to form a coherent representation of the sentence's overall meaning, a process referred to as semantic interpretation.

Incrementality of sentence processing   We often don't realize it, but human language processing occurs at remarkable speed. One key factor that enables this is our ability to process language input incrementally—that is, we interpret words and structures as we encounter them, without waiting for the end of the sentence. This holds true for both syntactic parsing and semantic interpretation. Frazier and Rayner [27] were the first to demonstrate this through reading eye-tracking. They found that sentences like (1b) induced processing difficulties compared to (1a), as evidenced by longer fixations on the disambiguating region (bold).

(1)   a.   Since Jay always jogs a mile and a half this **seems like** a very short distance to him.

   b.   Since Jay always jogs a mile and a half **seems like** a very short distance to him.

The prolonged fixations on the disambiguating region suggest that, when reading (1b), the reader—despite knowing the sentence hasn't ended—has already committed to (or strongly preferred) a specific syntactic analysis of the sentence (namely, interpreting "a mile and a half" as the object of "jogs"). When this interpretation turns out to be incorrect, the reader experiences difficulty at the disambiguating region, as the sentence structure conflicts with their initial parsing.

What we learn from difficulties   In general, syntactic parsing and semantic interpretation occur rapidly and effortlessly during reading, so much so that we are typically unaware of these processes. However, when these processes encounter difficulties and sentence comprehension breaks down, we gain valuable insights into the workings of the sentence processing system. Sentences like (1b) and (2), which initially present an appealing but incorrect syntactic analysis, are known as **garden path sentences**. The processing difficulties these sentences create have proven to be a powerful tool for studying how readers comprehend and resolve complex sentence structures.

(2)   The horse raced past the barn fell.

In a classic study about the time course of sentence comprehension, Sturt [28] tested whether reflexive resolution is guided by grammatical constraints (here, Principle A^2).

(3)   a.   The surgeon who treated *Jonathan* had pricked *herself* with a used syringe needle.

   b.   The surgeon who treated *Jennifer* had pricked *herself* with a used syringe needle.

In both (3a) and (3b), the reflexive pronoun must refer to *the surgeon*, following Principle A of binding theory. English stereotypes tend to associate surgeons with males, making the interpretation of the reflexive *herself* more challenging compared to the stereotype-consistent *himself*. The key question for Sturt, however, was whether readers consider the distractor noun phrase (*Jonathan* or *Jennifer*) as a potential antecedent for the reflexive. And if they do, whether this distraction occurs before or after grammatical constraints are applied.

In a series of experiments, Sturt found no effect of distractor gender on early measures, such as the first fixation durations, on the reflexive region. In other words, the initial time readers spend on reading *herself* is the same regardless of whether the distractor was *Jonathan* or *Jennifer*, suggesting readers were not considering the distractors to be possible antecedents at this stage. However, in a later measure—second pass duration—Sturt observed that a distractor matching the reflexive's gender (e.g., *Jennifer*) slowed down processing of the anaphor, indicating that at this late stage, readers may have briefly considered the possibility that *herself* referred to *Jennifer*. This finding supports the binding-as-an-initial-filter hypothesis, suggesting that readers use grammatical constraints in the early stages of resolving pronouns and anaphors. Nonetheless, the results also imply that, under certain conditions, readers may have ways to override binding principles if necessary.

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^{2}An anaphor must be bound in its binding domain.

Variability in eye movement measures

> "The terms"early" and "late" may be misleading, if they are taken to line up directly with first-stage vs. second-stage processes that are assumed in some models of sentence comprehension."[29]

Research on sentence processing using eye-tracking has long been challenged by the variability in eye movement measures. There is no clear mapping between eye movement patterns and cognitive processes during reading, and the same experimental manipulations can lead to markedly different eye movement patterns across studies. For instance, when an experimental manipulation yields early effects (such as changes in first fixation or gaze duration), studies often vary a lot in whether these effects are also accompanied by later effects [30].

Some potential explanations for this variability have been proposed. One is that readers are free to adopt different strategies to handle difficulties in sentence processing. Unlike word recognition, where the primary response to difficulty is to fixate longer on the word, sentence processing allows for a wider range of responses[30]. Readers may choose to reread earlier portions of the text, mentally process the difficult phrase further, or press ahead, hoping that upcoming information will clarify any ambiguity.

More recently, the long-standing assumption that the eye and the comprehension system (the parser) are tightly linked has been questioned. For instance, when readers regress during garden path sentences, this could be due to a general tendency for the eyes to return to familiar material due to difficulty, rather than the parser (selectively) reanalysing the previous text [31]. On this matter, some have proposed new eye-tracking measures that can target this distinction, for example the scanpath analysis [32]. Once the connection between the eye and the parser is more clearly understood, and we gain a better grasp of the underlying sources of eye movements during reading, it may become easier to explain the substantial variability in eye movement measures.

Further readings

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