Eye movements and morphological processing in reading

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In this article, I will give an overview of eye tracking studies on morphological processing since 2005 and a few earlier studies. An earlier survey article of Pollatsek and Hyönä (2006) covers almost all studies until then, but a number of interesting articles have been left undiscussed or were published after 2005. Before that, I will discuss (a) the advantages of studying morphological processing by means of eye tracking; (b) methodological issues related to eye movement experiments on morphological processing; (c) the dependent measures one can extract from the eye movement record and how they can be used in assessing the time course of morphological processing; (d) the boundary paradigm that has been used in morphological processing studies. I will argue that eye tracking should be used more often in morphological processing research, since it allows for studying morphologically complex words in a natural way and at the same time its rich data output allows for deeper levels of analyses than some other methods do.

Keywords: eye movements, morphology, methodology, reading, boundary paradigm

Until recently, most research on visual processing of morphologically complex words used single word paradigms such as naming and lexical decision, fairly often in combination with masked or overt priming. However, of late, other paradigms have been employed to study the role of morphology in complex word processing. One such paradigm is eye movement registration during reading. This paradigm has become very feasible, since eye tracking technology has developed to a stage that an accurate spatial and temporal on-line record can be obtained for each and every word, no matter whether it appears in isolation or in context. Typically, however, eye movement registration has been used to study word processing in context and this is the case for morphological processing studies as well. In the below, I will give a survey of the history of eye movement studies on morphological processing.

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In addition, I will discuss the advantages of eye movement studies, how they are set up and what dependent measures can be extracted from the eye movement record. Before discussing these issues I will give a short general introduction about eye movements in reading.

Basic knowledge about eye movements in reading

In Figure 1, an eye movement record of a hypothetical adult reader is presented. As can be seen from this record, during reading we do not slide our eyes over the text, but make eye movements, called *saccades*. After every saccade, our eyes remain fixated for a moment on a specific location to extract information from the text. During a saccade, the reader does (almost) not extract any information, a phenomenon that is called *saccadic suppression* (Matin, 1974). The duration of a saccade depends on its length, but in reading a saccade is typically completed between 20 and 30 ms. The duration of a fixation during reading an alphabetic language is most often between 200 to 300 ms, but they may be shorter or longer as well. Most words are dealt with in one single fixation, but longer words (like *movements* in Figure 1) are often read with two (or more) fixations, increasing the overall reading time for such words. Short and frequent words (such as the words *on* and *has* in Figure 1) are often skipped. Most often the eye makes forward saccades, but about 15% of the saccades go backwards (so-called *regressions*, here from the word *revealed* to the word *has*). In the eye movement record presented in Figure 1 (which is quite a typical record for an adult reader), fixation durations run from 150 to 303 ms, which means that the first eleven words were read in less than three seconds. Fixations are often located in the middle of a word (or slightly left of the center). This position is termed *the optimal viewing position* (O'Regan, 1992), since it is the position from which a word can be processed fastest. The word length of an upcoming word can be estimated during the previous fixation; as a result, an oculomotor program can be targeted to the optimal viewing position of that word. Taken together, one may conclude that the work of the eyes during reading is highly efficient, allowing information to be extracted rapidly, and thereby making reading a dynamic and fast activity.

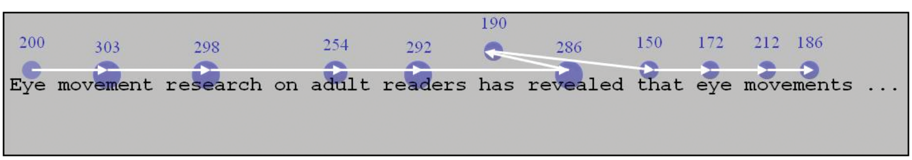

Figure 1. An eye movement record of an adult reader on part of a sentence. The blue dots represent fixations, the white arrows represent saccades, and the numbers represent fixation durations.

Eye movement studies on morphological processing until 2005

There is a long tradition of using eye movements in psycholinguistic research (for a survey, see Rayner, 1998, 2009). However, it took some time before the first eye movement studies on morphological processing appeared. More specifically, the study of morphological processing by means of eye movements started in the late eighties (Inhoff, 1989; Lima, 1987), continued to some extent in the nineties (Beauvillain, 1996; Hyönä & Pollatsek, 1998) and gained real momentum in the next millennium (see Pollatsek & Hyönä, 2006, for a survey).

The first studies (Inhoff, 1989; Lima, 1987) were mainly concerned with the question whether morphological information is parafoveally encoded or not. More specifically, it was asked whether, in a noun phrase like '*The exhausted cowboy…*', morphological constituents such as *cow* were extracted while the previous word *exhausted* was still fixated. The paradigm that was used to study this question was *the eye-contingent boundary paradigm* (Rayner, 1975), a paradigm that I will come back to in more detail. Similar to what was found much later by Kambe (2004) in English and Bertram and Hyönä (2007) in Finnish, both Lima (1987) and Inhoff (1989) did not find evidence that morphological information is parafoveally encoded (but see Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2000, 2005, for evidence of parafoveal morphological information extraction in Hebrew).

The second wave of eye movement studies dedicated to morphological processing tapped into the question of how complex words — especially compounds — are processed while they are fixated. In their survey article Pollatsek and Hyönä (2006) come to the conclusion that the results obtained in eye movements studies are best accommodated by a dual-route model that assumes that there are two routes to encode multi-morphemic words, a compositional route and a holistic route. The compositional route involves segmenting a complex word into morphemic constituents, subsequently accessing these constituents and then 'putting them together somehow'. The holistic route involves access to the complex word as a whole.[1]

The authors further argue that most of the findings in eye tracking studies are in line with the visual acuity hypothesis put forth by Bertram and Hyönä (2003). This hypothesis holds that the way a complex word is accessed depends to a great extent on its length. Longer words are more likely to be accessed via the compositional route and shorter words via the holistic route. Shorter words of eight characters or less are typically dealt with in one fixation during which most or all letters fall within the area of foveal vision, which allows for retrieval of the word as a whole. For longer words at least one additional fixation is required in order for letters in the end of the word to be foveally inspected. The visual acuity hypothesis holds that readers make use of the first constituent in processing long compounds simply because initially they do not have enough letter information available on the latter part of the word.

Pollatsek and Hyönä (2006) also point out that eye movement studies have found that segmentation of compounds into their constituents is facilitated by explicit segmentation cues. For instance, in Finnish, Bertram, Pollatsek, and Hyönä (2004) found that compounds with vowels of different vowel quality around the constituent boundary (e.g., *jäätelöauto* 'icecream car', with front vowel *ö* and back vowel *a* around the boundary) are processed faster than compounds with the same type of vowels throughout (e.g., *inflaatiouhka* 'inflation threat', with back vowels throughout the word). Finally, Pollatsek and Hyönä note that findings of eye movement studies converge on the minor role of semantic transparency in processing Finnish and English compound words (Frisson, Niswander-Klement, & Pollatsek, 2008; Pollatsek & Hyönä, 2005).

The studies before 2005 that were not covered by Pollatsek and Hyönä and the studies after 2005 that will be discussed in this article partly come back to the same issues, but partly deal with new questions. Before discussing these studies in some detail, I will (a) outline the advantages of studying morphological processing by means of eye tracking; (b) discuss methodological issues related to eye movement experiments on morphological processing; (c) discuss the dependent measures one can extract from the eye movement record and how they are linked to the time course of morphological processes; (d) discuss the boundary paradigm that has been used in morphological processing studies.

Advantages of studying morphological processing by means of eye tracking

Most eye tracking studies on morphological processing have studied complex word processing in sentence context. As far as I know, there are only three studies that deviate from this practice. Hyönä, Laine, and Niemi (1995) conducted a naming and a visual lexical decision experiment combined with eye-tracking to investigate the processing of Finnish inflected and derived words in comparison to monomorphemic ones. Beauvillain (1996) presented prefixed or suffixed words to be read, followed by a semantically related or unrelated word at the right side of the complex word. The subjects' task was to indicate whether the two subsequent words were semantically related or not. Kuperman, Schreuder, Bertram and Baayen (2009) conducted an eye-tracking experiment with 2,500 Dutch compounds presented in isolation for visual lexical decision while readers' eye movements were registered. All other studies reviewed here and in Pollatsek and Hyönä (2006) are studies in which morphologically complex words are inserted in sentential contexts, offering a close-to-natural setting for these words to be read. Typically participants in these studies are instructed to read sentences for comprehension and are occasionally asked to indicate what the sentence was about.

A clear advantage of eye movement experiments is that a large number of dependent measures can be extracted from the eye movement record. Whereas in single word paradigms dependent variables are restricted to response latencies and error rates, the eye movement record provides several fixation duration and fixation location measures, which can be considered individually or in combination. I will discuss these possibilities in detail in the section on dependent measures.

Another advantage is that complex words can be offered under normal text reading conditions. That is, people typically read morphologically complex words in sentence context rather than in isolation. Moreover, readers typically read words and sentences for comprehension, which is required in most eye movement studies rather than contemplating whether a string of letters forms a word or a nonword, as required in a lexical decision task. In their eye movement study on morphology, Andrews, Miller, and Rayner (2004) put it like this:

> "A more general problem with all of the results reviewed is that they have been obtained in word judgment tasks that require task-specific decision processes that may, themselves, be sensitive to morphological complexity. Decomposition effects in the lexical decision task, one of the most frequently used paradigms, might arise from postlexical decision processes invoked to deal with the specific decision requirements of the task (Balota & Chumbley, 1984) and the stimulus context in which they are presented (Andrews, 1986)." (p. 289)

In addition to this, reading words in isolation deprives a reader of information that may modulate the role of morphology in complex word recognition. Two kinds of information have been identified. First, it is known that on many occasions orthographic (and phonological) information of a word is partially processed before a word is fixated. If, for instance, a phrase like '*My previous girlfriend…*' is read, it is likely that a reader has already extracted the identity of the first letters of *girlfriend*, while still fixating *previous*. In comparison to single word studies, this preview benefit may moderate the time course by which morphological or whole-word information becomes available, since the time to perform the orthographic analyses is reduced. Second, a reader often extracts the length of a word, before it is fixated. In my example it would mean that the reader would estimate the length of the word *girlfriend* while fixating the word *previous*. This information is used to target *the optimal viewing position* (OVP) of a word, which resides at the word centre or slightly left of the word centre. Indeed, the majority of initial fixations lands slightly left to the word centre, although initial fixations on longer words tend to be more leftward oriented. The most typical landing position for the word *girlfriend* would be somewhere around the constituent boundary, between the 'l' and the 'f'. It could be hypothesized that the landing position is important for the speed with which morphological information can be extracted (see Bertram et al., 2004, for an example). Single word paradigms typically do not provide word length information, before a complex word is fixated and this discrepancy with sentential context studies may lead to different results between the two types of studies (see Rayner, 1998, 2009, for a survey on preprocessing orthographic and word length information as well as on the OVP-literature).

Given all this, I believe that the burden of proving whether morphological effects are real or not lies more on single-word studies than on the kind of eye movement studies I am reviewing here. This is not to say that there is no convergence on the role of morphology in eye movement studies and single-word studies (see e.g., Juhasz & Berkowitz, in press; Kuperman, Bertram & Baayen, 2008; Kuperman et al., 2009; Paterson, Alcock, & Liversedge, in press). However, for all the reasons mentioned above, one should be cautious in interpreting results obtained in the latter type of studies.

Methodological issues related to eye movement experiments on morphological processing

Selection of experimental materials

With respect to the selection of experimental materials, an eye movement experiment investigating the role of morphology in complex word recognition in sentential context is in many ways the same as a single-word experiment. In a factorial design, one would take care that there is an orthogonal contrast in the manipulated factor(s) (e.g., first constituent frequency), while controlling for other potentially confounding factors (e.g., word length, second constituent frequency, and whole word frequency). In a regression design, one would take care that there is a good distribution in the variables of interest. Most eye movement experiments that have been conducted have made use of the factorial design. In such designs there are — apart from lexical-statistical variables pertaining to the word — a number of sentence-related variables that need to be controlled for. Typically, complex target words of different conditions (for instance, a compound with a high-frequency first constituent and a compound with a low-frequency first constituent) are inserted into a sentence frame that is similar up to word N+1, the word following the target word. This is done in order to avoid potential influences of sentence context on the processing of the target words. Similarly, several pretests are conducted to equate different conditions on other potential sentence-related variables. One pretest assesses the predictability of a given target word given the previous context and another the naturalness of the sentence, both of which should be equated across conditions (typically, the predictability of the compounds is zero or close to zero). In regression designs, one may include ratings or sentential properties (e.g., number of words before target word, length and frequency properties of previous and subsequent words) in the statistical models as control variables. No matter what the design, one should take care that target words are neither located at sentence or line beginnings nor at sentence or line endings, due to possibly confounding start-up or wrap-up processes (see Kuperman, Dambacher, Nuthmann, & Kliegl, 2010, for a recent exploration of start-up and wrap-up processes). Questions — either in written format incorporated in the experiment or verbally — should be asked in order to check whether subjects have understood what they have read.

Running the experiment

With respect to running the actual experiment, a few things should be taken into consideration. First, it is important to use an eye tracker with a good temporal resolution. Since effects can be as small as 10 ms (first fixation duration effects for instance), it would be good to use an eye tracker with a high sampling rate. Typically, eye trackers that used to study morphological processing have a sampling rate from 250 to 1000 Hz. Since morphological processes may also be reflected in fixation locations or intraword saccades (the jump from one location in a word to another), a good spatial resolution is also required.[2] Second, it is important to calibrate the subject's eye very well. The better the calibration, the less data needs to be cleaned or thrown away. Third, all eye movement experiments on morphological processing have made use of monocular eye tracking. If calibration of the eye intended to track does not succeed (very well), one may consider tracking the other eye. Binocular eye tracking is not needed, since eye movements of the left and right eye are pretty well aligned (but see e.g., Liversedge, Rayner, White, Findlay, & McSorley, 2006, for a slightly different view).

Data cleaning before analyses

With respect to data cleaning, there are a number of things that one should pay attention to. First, particular fixations within the eye movement record or the eye movement record as a whole may be shifted. As long as these shifts appear to have happened on the vertical plane only, there is no problem and fixations may be shifted up or down to the word area. Horizontal shifts are more problematic and the safest way to deal with horizontally mislocated fixations is to exclude the whole track. Short-lasting fixations on a word that are located within one or two characters from a neighboring fixation are best integrated with this neighboring fixation to create one single longer fixation.[3] This is because most likely these fixations are not a result of a real saccade, but a result of jitter or blinks during the neighboring fixation. Other short-lasting fixations are typically excluded from the eye movement record since it is assumed that these fixations have landed on unintended locations and that no real cognitive processing happens during these fixations. In compound studies using compounds of considerable length (more than 12 characters) I also have sometimes excluded cases where there is one single fixation on the target word followed by an immediate regression to a previous word, despite the single fixation being longer than 100 ms. Since, in general, longer words elicit more than one fixation, I have taken such instances as so-called overshoots in which the motor program targeted the previous word, but ended up in the beginning of the long compound word. Finally, readers sometimes blink their eyes and create new fixations as a result. This often produces short fixation durations at one or either side of the blink and these fixations can be incorporated in a fixation in close vicinity of the short-lasting fixation or — as is done by many researchers — these trials can be excluded altogether.

Eye movement measures assessing the time course of morphological processes

As noted above, a great advantage of tracking the eye while processing complex words is that a large number of dependent variables can be extracted from the eye movement record. In Figure 2, a hypothetical eye fixation record on the phrase '*My previous girlfriend is…*' is presented. Suppose that in this phrase the compound word *girlfriend* is target word N and that it attracts five fixations. Five fixations on a word like *girlfriend* are quite unlikely, but this number is needed to explain most of the eye movement measures that can be extracted from the eye movement record on a morphologically complex word. In the example each circle reflects a fixation and the numbers in the circle reflect the ordinal appearance of each fixation. In other words, the eye fixation record here shows an initial fixation on the word *My*, a subsequent fixation on the word *previous*, followed by three fixations on the target word *girlfriend*, followed by a regressive fixation to the word *previous*, a subsequent fixation on the target word *girlfriend* again, followed by a fixation on word N+1 *is*, followed by a final fixation on the target word *girlfriend*. Suppose further that *girlfriend* represents the high-frequency first constituent condition and that it is pitted against a word like *hairstyle*, representing the low-frequency first constituent frequency condition (in fact, *hair* is not a low-frequency word, but in comparison to *girl* it is). Given that we use a factorial design with which we try to obtain a first constituent frequency effect, suppose that we include *hairstyle* in the same sentence frame as girlfriend: '*My previous hairstyle is …*' and all other properties of *hairstyle* and *girlfriend* are matched (e.g., length of constituents and whole word length, frequency of second constituent and whole word frequency). In order to find a first constituent frequency effect, one can consider eye movement measures that relate to fixation durations, fixation locations and fixation probabilities. I discuss these measures below in relation to the time course of morphological processing, assuming that a first constituent frequency effect reflects that the first constituent is accessed in the course of compound processing.

Parafoveal-on-foveal effects

The earliest measure that may show a frequency effect is *the gaze duration* or *the final fixation duration* on word N−1 (in this case the duration of the only fixation on the word *previous* in first-pass reading; note that when there is only one fixation on a word in first-pass reading, first fixation, single fixation, final fixation, gaze, and selective regression path are equivalent). An effect of word N reflected in a measure on word N−1 is called *a parafoveal-on-foveal effect* (the PoF-effect, a term introduced by Kennedy, 1998) and in this case that would mean that morphological information of word N is already extracted during the processing of word N−1. However, PoF-effects across words are typically hard to find (see Rayner, White, Kambe, Miller, & Liversedge, 2003, for a survey).

Another early measure that may be considered is *first fixation location*. If average first fixation location were further into a high-frequency first constituent than

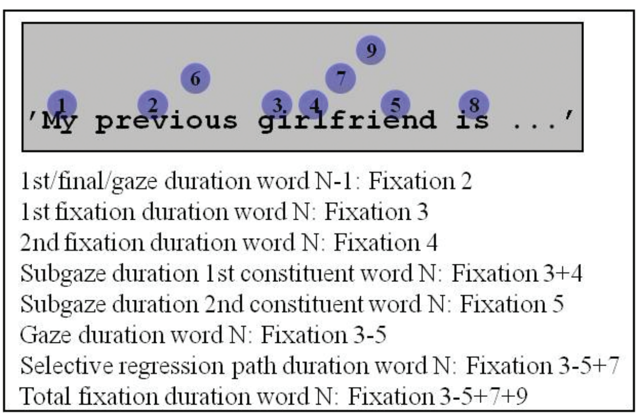

Figure 2. Hypothetical eye fixation pattern on the sentences phrase 'My previous girlfriend is …' and eye fixation measures that can be derived from these fixations for pre-target word N−1 ('previous') and target word N ('girlfriend').

a low-frequency first constituent compound, it would mean that morphological information of word N was extracted during the final fixation on word N−1, since it is during this fixation that a decision where to saccade to is being made. Typically, there are no first fixation location effects on a morphological level (but see Hyönä & Pollatsek, 1998, Experiment 2, for an exception). Finally, one may consider the skipping rate of word N as a measure of early processing. However, as far as I know, there is no evidence in eye movement studies on morphology that show a skipping effect as a function of morphological properties of word N. In sum, in general there is little evidence that morphological information of word N is preprocessed on word N−1 in alphabetic languages.

Early processing measures on the target word

On the target word itself, eye movements can give a clear insight into the time course of morphological processing. In particular, eye movements may be able to separate effects at an early processing stage from effects at a later processing stage. However, such a distinction is not always possible and if it is possible, it should be noted that data should be treated with caution in order to do so. For instance, one may be tempted to consider first fixation duration as the earliest durational measure (fixation number three). However, here one should be warned that first fixation duration is not an easy measure, since there are cases where the first fixation is the only fixation, but there are also cases where it is the first of multiple fixations on the target word (as in our example). In other words, some subjects may read 'girlfriend' in one fixation, other subjects may read it in more than one fixation. What is important then is to take the probability of making a second fixation into account. In the case of longer words, subjects typically use two or more fixations to process them. For instance, all studies of Hyönä and colleagues in which compounds of twelve characters or more are used, the probability of making a second fixation is around 90%. In this case one can be sure that an effect in first fixation duration reflects an early effect. In case of shorter words that occasionally elicit multiple fixations, it may be wise to analyze the first of multiple fixations separately, as they may offer one a window into the early stages of processing.

Another measure that could reflect early processes is the subgaze duration on the first constituent. This measure can be defined as the sum of durations of first-pass fixations on the first constituent. With first-pass fixations I mean the first fixation on the first constituent and any subsequent fixation on this constituent before the eye moves to the next constituent or another word. This is a good measure, because it incorporates the probability of making a second fixation as well as the location of the second fixation as an indicator of more effortful or less effortful processing. In case of our example, one may expect that — if the first constituent is addressed during lexical access — high frequency first constituents require less processing effort than low-frequency ones. As already indicated above, this may be reflected in fixation duration, but it may also be reflected in second fixation location and the probability of making a second fixation. More specifically, if the first constituent is easy to process initial fixation duration(s) may be shorter, but it is also less likely that a second fixation will be made on it and at the same time it is more likely that — if a second fixation is made — it is further in the word. It is important to realize that the decision to make a second fixation and the decision where to locate the second fixation are made during the first fixation. In our studies, low-frequency first constituent compounds typically elicit more often a second fixation on the first constituent than high-frequency ones, leading to longer first constituent subgaze durations (e.g., Kuperman et al., 2008).

One may also look at the length of the first intraword saccade (the saccade from the first to the second fixation) or the probability of making a second fixation as indexes of early processing, although in principle these two measures are captured in the subgaze duration of the first constituent. However, sometimes it may be more insightful to consider these measures separately.

Later processing measures on the target word

With respect to later measures on the word, one could consider the subgaze duration of the second constituent, but again, one needs to know the number of fixations on a word to decide if this measure is a good index of later processes or not. In case of longer words typically eliciting two or more fixations, it is, but in case of shorter words the number of multiple-fixation cases may be too small for subgaze duration of the second constituent to give an insight into later stages of processing. Later individual fixation durations such as the second fixation duration can also be problematic, because of the fact that a) there may be an unequal amount of second fixations between conditions; b) second fixations followed by a third fixation may be more frequent in one condition than in another condition and we know that fixations that are followed by a subsequent fixation are typically shorter than those that are not; c) second fixations in one condition may be on average in a different location than those in another condition. Unfortunately, all these potential problems may make the second fixation duration difficult to interpret as an index of later processing.

My recommendation therefore is — especially with shorter complex words — to look at gaze duration in relation to first fixation duration as an index of later processing in first-pass reading. If there is an effect in first fixation duration that is similar in size to the gaze duration effect, one may conclude — if there are enough multiple fixation cases — that the effect was early and that later processing stages did not contribute to the effect. However, if there is no effect in first fixation duration, but a solid effect in gaze duration, one can be fairly sure that the effect started to arise at later stages of processing. In general, one can say that the interpretation of first-pass eye movement measures is not as straightforward as one may initially think and that a careful consideration of what they may reflect is called for. However, when doing so, most often the eye movement record will be able to disentangle early stages of processing from later stages.

Measures reflecting integration of target word into sentence context

Other measures that I will discuss here relate to or include later-pass fixations, typically (but not necessarily) reflecting measures that tap into the stage of integration of the target word into the sentential context.

One such measure is *regression path duration* (sometimes referred to as *go-past time*), the time it takes from the first fixation on the target word to the last fixation on the target word before exiting the word to a word located at the right side of the target word. In Figure 2 this measure includes fixations three to seven. In comparison to gaze duration, this measure includes fixations that fall on previous words (here only fixation number six) as well as fixations on the target word after the target word has been exited to the left (here only fixation number seven).

In order to restrict themselves to processes that are directly related to target word processing, more often morphological processing researchers consider the *selective regression path duration (SRPD)*, a measure that includes only the fixations that fall on the target word before exiting the target word to the right (here fixations three to five plus fixation number seven). Both measures may tell you something about the difficulty of integrating the target word into the unfolding sentence representation, but also, this measure should be considered in relation to gaze duration. If the effect in gaze duration is equal in size as the effect in (selective) regression path duration, one cannot conclude that the effect reflects sentence integration processes. Only when the effect is smaller or bigger in SRPD than in gaze duration can one conclude that there is an effect related to such integration processes.

Perhaps purer measures reflecting integration processes are the probability of regressing back to an earlier word in the sentence and the time a reader spend on the target word in the second pass before exiting to the right (SRPD minus gaze duration– the duration of fixation number seven in this case). Whereas it is likely that the measures mentioned here reflect sentence integration processes, they may — to some extent — also still reflect word processing difficulties. That is, if a word is very difficult to process (for example, if it is novel to the reader) a reader may leave the word at an early stage in order to get additional support from previous context. For instance, in studies on compound processing with the boundary paradigm, which I will discuss below, the manipulation of a second constituent may generate the feeling that the fixated compound will be very hard to process and regressions back may reflect a 'roll-up-the-sleeves' strategy to deal with the word in a second pass.

The final measures I discuss here relate to or include fixations that are launched to the target word after this word has been exited to the right. One such measure is *total fixation duration*, the sum of all the durations of the fixations on the target word. In comparison to SRPD, this measure includes all fixations on the target word, no matter whether and how many times the word has been exited. In the example in Figure 2, total fixation duration is the sum of fixations three to five, fixation number seven and fixation number nine. Again, this measure should also be considered in relation to other global measures such as gaze duration and selective regression path duration. If one considers total fixation duration in relation to gaze duration one may be able to assess the global difficulty a reader has in integrating the word into the sentence; relating total fixation duration to SRPD may give one an idea of how well the word fits in with the remainder of the sentence. One may also consider the probability of regressing back to a target word or the regression time (the duration of fixation 9 in this case) as a late sentence integration measure. However, one should be very cautious in the interpretation of these very late measures, since the effects in these measures may be confounded with the properties of words and sentence syntax after the target word, which are typically not controlled for.

The boundary paradigm in morphological processing studies

The eye-contingent boundary paradigm (Rayner, 1975) is a paradigm designed to assess the type and amount of information that readers may extract from the parafovea. In this paradigm, there is typically a control condition in which nothing changes during reading and one or more change conditions in which parafoveal information is manipulated. A classic study with the boundary paradigm — which I will use to illustrate it — is the study of Rayner, Balota, and Pollatsek (1986). In this study, Rayner et al. tried to establish whether readers extract visual-orthographic and/or semantic information from parafoveal words. To that end, they created four conditions: three change conditions and one no-change or correct condition (see Table 1). The correct condition (*song*) is the baseline against which the change conditions are compared. In the change conditions, there is an invisible boundary placed to the left of the parafoveal letter string (which is either a word or a nonword). During the saccade crossing the invisible boundary, the word or nonword is changed into the correct form (see Figure 3).

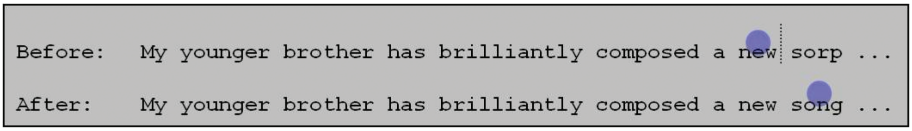

Figure 3. A change condition before and after crossing the invisible boundary. During the saccade launched from word N ('new') the parafoveal preview 'sorp' changes into 'song'. Example taken from Rayner et al. (1986)

Table 1. The Four Conditions from the Boundary Experiment of Rayner et al. (1986). The Critical Word is Shown in Italics

Preview Condition	Sentence	Gaze *Song*
Correct	My younger brother has brilliantly composed a new *song* for the school play.	246
Semantically related	My younger brother has brilliantly composed a new *tune* for the school play.	286
Orthographically related	My younger brother has brilliantly composed a new *sorp* for the school play.	251
Unrelated	My younger brother has brilliantly composed a new *door* for the school play.	290

Because vision is suppressed during saccades, the reader does not become aware of the actual change. The change conditions that Rayner et al. used were conditions in which the parafoveal word or nonword was either semantically related (*tune*), visually-orthographically related (*sorp*) or unrelated (*door*) to the word in the correct condition (see Table 1).

Assuming that the unrelated word does not generate any parafoveal processing advantage, the question is how much benefit is gained when seeing a preview that is semantically or orthographically related. Rayner et al. found that orthographically related previews facilitated target word processing to the same extent as the correct condition, whereas semantically related previews yielded no benefits for target word processing. Both effects are interesting. First, it is notable that even relatively short words are not processed in the parafovea up to a semantic level. Second, it is notable that a change of the final two letters into letters that are visually but not orthographically similar does not harm target word processing. This suggests that the final letters of a parafoveal word are not analyzed up to the orthographic but only up to the visual level (that is, they seem to be encoded in terms of coarse visual shape only). Several other studies confirm this to be the case and also confirm that the first two to three letters of a parafoveal word are encoded up to the orthographic level (see Hyönä, Bertram, & Pollatsek, 2004, for a survey of these studies). As we will see later, both the lack of a semantic preview effect

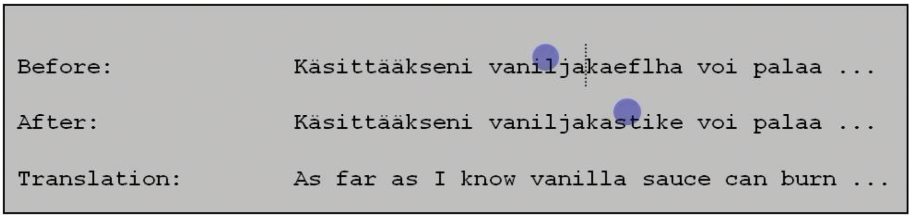

Figure 4. A change condition before and after crossing the invisible boundary. During the saccade launched from the first constituent ('vanilja') the parafoveal preview 'kaeflha' changes into 'kastike'. Example taken from Hyönä et al. (2004).

and the encoding of final letters up to the visual level only do not replicate in the within-compound boundary paradigm.

As noted earlier, similar boundary paradigms across words were employed in the eighties to investigate to what extent morphology is processed in the parafovea, using compound words as *cowboy* as one of the parafoveal preview conditions (Inhoff, 1989; Lima, 1987). Hyönä et al. (2004) were the first ones to use the boundary paradigm within complex words. In their study, they used compound words of considerable length (twelve to eighteen characters) with either a high or low frequency first constituent and presented these compounds in a change or a no-change condition. The change condition was similar to the visual-orthographic condition in Rayner et al. (1986) in that — in comparison to the no-change condition — the first two letters of the second constituent were preserved and the rest of the letters were replaced by visually similar letters. They inserted an invisible boundary at the constituent boundary and the replaced letters were replaced by the correct letters as soon as the eye crossed the invisible boundary (see Figure 4).

Hyönä et al. found that this type of manipulation led to a processing advantage of about 100 ms. for the no-change condition, showing that the final letters of the second constituent are encoded beyond the visual level. That is, if only low-level visual information would have been extracted of the final letters, there should have been no effect of display change, similarly to what was found across words when replacing *song* by *sorp* in the parafovea (Rayner et al., 1986). Subsequently, comparable kinds of boundary studies with compound words were conducted by White, Bertram, and Hyönä (2008), Juhasz, Pollatsek, Hyönä, Drieghe, and Rayner (2009) and Drieghe, Pollatsek, Juhasz, and Rayne (2010). I will discuss these and other morphological processing eye movement studies in the next section.

It should be noted that in general these kinds of boundary studies require that both the first and the second constituent of a complex word be of considerable length. This ensures that they are both going to be fixated frequently, which in turn ensures reliable data analyses. Given the fact that prefixes and suffixes are typically quite short, but that both constituents of a compound word may be quite lengthy, this type of experiment is more easily constructed with compound words than with prefixed or suffixed inflections or derivations. However, derivations with longer productive prefixes or suffixes (such as *-ness* in English) may also be quite suitable for eye-contingent invisible boundary experiments.

Eye movement studies on morphological processing since 2005

In this section I will discuss the morphological processing eye movement literature that has appeared since 2005 and some studies that appeared a bit earlier. I will discuss most of these studies in the light of the time course of morphological information extraction. As noted earlier, eye movement studies are extremely suitable to assess at what point in time morphemic and/or whole-word information becomes available.

The discussion has three parts. First, I will come back to the question whether morphological information is extracted across words from the parafovea. Second, I will discuss when constituent and whole-word information become available in the processing of compound words once they are fixated. Third, I will discuss eye movement studies that have dealt with other morphological issues than the processing of compound words.

Does parafoveal morphological information extraction across words exist?

As noted above, the earliest eye movement studies on morphological processing were boundary studies concerned with understanding the extent to which morphological information is parafoveally encoded (Inhoff, 1989; Lima, 1987). Neither study found evidence for parafoveal morphological information extraction, but studies by Deutsch and colleagues showed significant benefits from having a parafoveal preview of the word's morphological root in Hebrew (Deutsch et al., 2003; Deutsch et al., 2000, 2005). Inspired by these studies, Kambe (2004) reinvestigated the issue in English using stronger manipulations than in previous studies. For instance, she used change conditions in which the morpheme boundaries were demarcated in a highly salient way (e.g., by using capital Xs, *reXXXX*). She also investigated whether there was a morphological preview effect when the launch distance was very near (that is, when fixations on preceding words were close to the word end). However, even under these in principle favourable circumstances, the morphological preview benefit failed to show up. Kambe suggested that the morphological richness of Hebrew in comparison to English was one of the reasons for the difference between Hebrew and English results. She speculated that effects in alphabetic languages may be found, but only in case of languages that are morphologically productive.

Since Finnish is such a language, Bertram and Hyönä (2007) decided to investigate the issue in this language. They embedded compound words with long or short first constituents in sentences, for which they manipulated the amount of information available of the first constituent before the compound word was fixated. In the change conditions, the first three to four letters were offered parafoveally. These letters coincided with the whole first constituent in case of short but not in case of long first constituents. They hypothesized that if readers would extract morphological information from this preview, the change manipulation should be less detrimental in comparison to the no-change condition for short than for long first constituent compounds. However, the fact that this was not the case (not even when the launch position was nearby) indicated that in reading Finnish there is no morphological preview benefit either. It thus seems that a language's morphological productivity is not a decisive factor for morphemes to be extracted parafoveally. Characteristics of a script may be more decisive. In Hebrew for instance, the root morpheme is typically visually distinct from the vowel pattern, since vowels are indicated by diacritic marks above or below consonants or not at all. In other words, from a visual point of view it is typically easier to extract the root morpheme in Hebrew than in alphabetic languages like English and Finnish and therefore it is understandable that morphological effects start to appear earlier in the former than in the latter type of language. Further confirmation for this viewpoint comes from a study by Yang, Slattery, and Rayner (2009) in Chinese, who found that also Chinese readers access morphemic information of two-character target compounds parafoveally, even up to the semantic level. Given that both Chinese and Hebrew visually separate individual morphemes, these findings suggest that visual segmentability of morphemes is the key factor in parafoveal morphological information extraction.

Availability of constituent and whole-word information in compound word processing

In the past few years, several eye movement studies have been conducted to establish if first constituent, second constituent and whole-word information becomes available during compound processing, and if so, when. Three main experimental techniques have been used in these studies. First, the frequency of both constituents and the whole word has been manipulated in order to assess whether either of the constituents or the whole-word form participates in compound processing. Second, a number of eye movement studies have investigated whether segmentation cues like hyphens or spaces facilitate compound processing by making constituent information earlier available. Finally, a number of eye-contingent boundary studies have been conducted in order to assess when and to what extent information on the second constituent comes available. In all these studies eye movement measures reflecting earlier and later processes have been considered.

To start with the *first constituent*, it may come as no surprise that many studies report early first constituent frequency effects. For instance, Kuperman et al. (2008, 2009) report a first constituent frequency effect for respectively Finnish and Dutch compounds in both first fixation duration (FFD) and subgaze duration on the first constituent (SubgazeC1). Similarly, Pollatsek, Bertram, and Hyönä (in press) found first constituent frequency effects for both novel and existing Finnish compounds in early measures of processing (FFD, SubgazeC1). In all of these experiments, compounds were relatively long (twelve characters or more) and typically required two or more fixations. As argued by Bertram and Hyönä (2003), this situation gives the first constituent a visual acuity benefit over the second constituent and the whole word, since it is typically the only part of the word that falls within foveal vision on the first fixation.

In English, first constituent frequency effects (like first constituent family size effects) are typically harder to obtain and if obtained they are smaller in size and obtained under special circumstances. For instance, Inhoff, Solomon, Starr, and Placke (2008) found first constituent frequency effects for compounds in which overall meaning is more connected to the first than the second constituent (so-called *headed compounds*, e.g., *humankind*), but not for compounds in which the second constituent is the main determinant of meaning (so-called *tailed compounds*, e.g., *armchair*). The first constituent frequency effect for headed compounds was found in FFD and got enlarged in gaze duration (Gaze), but it was notable that the effect in FFD only appeared for compounds with a low-frequency second constituent. Similarly, Juhasz (2007) found a first constituent frequency effect for both semantic and opaque compounds in both FFD and Gaze, but again the effect in FFD was only present for compounds with a low-frequency second constituent. Juhasz and Berkowitz (in press) found a small but significant first constituent family size effect (17 ms) in Gaze, but a non-significant tendency for this effect in the FFD of multiple fixation cases (8 ms). The compounds in English studies are typically shorter than the ones used in Finnish and Dutch studies, so given the visual acuity hypothesis of Bertram and Hyönä (2003) it is understandable that first constituent frequency effects are hard to obtain in English. Also in Finnish Bertram and Hyönä (2003) failed to observe a first constituent frequency effect for compounds around eight characters. Juhasz (2007) comments of the first constituent frequency effect that she did find in English, that "the inclusion of longer compound words in the present experiment may have resulted in more robust beginning lexeme (=constituent) effects" (p. 384) (but see Juhasz, 2008, for an exception on this general pattern). Taken together, it seems that first constituents only actively participate in short compound processing when they are a prominent source of information, for instance when they prominently contribute to compound meaning or in the context of a long compound or a low-frequency second constituent.

With respect to the *second constituent*, frequency effects typically arise later for compounds of considerable length, but arise earlier for shorter compounds. Kuperman et al. (2008, 2009) found second constituent frequency effects in the subgaze duration on the second constituent (SubgazeC2), but not in FFD or SubgazeC1. Several boundary studies have also shown that second constituent information comes available relatively late. In line with earlier studies (Hyönä et al., 2004; Juhasz et al., 2009; Pollatsek & Hyönä, 2005; White et al., 2008), Drieghe et al. (2010) did not find manipulations of the second constituent to affect measures reflecting early processing (FFD, SubgazeC1). However, all these studies do show robust change effects on the second constituent. This pattern of results reflects the fact that the second constituent is processed while the first constituent is fixated, but that the first constituent is processed first. This is possible because attention shifts (from the first to the second constituent for instance) can precede actual eye movements (from the first to the second constituent for instance, see Rayner, 1998). Again, almost all of these studies included long compounds with an average of eleven characters or more (with the exception of Drieghe et al., 2010). For shorter English compounds second constituent frequency effects are also found, but they tend to appear earlier. Both Juhasz (2007) and Inhoff et al. (2008) found second constituent frequency effects in FFD, but also these second constituent frequency effects seem to appear under special circumstances. Inhoff et al. (2008) found an early second constituent frequency effect for tailed but not headed compounds and both Inhoff et al. and Juhasz (2008) found the early second constituent frequency effect in case the first constituent frequency was of low frequency. If we average over the opaque and transparent compounds of Juhasz and the tailed compounds of Inhoff et al., the effect was 1 ms in case of high-frequency first constituent conditions, but 23 ms in case of low-frequency first constituent conditions. Again it seems that the role a constituent plays in compound processing depends on several other factors. Finally, there is one boundary study (Häikiö, Bertram, and Hyönä, 2010) that found an effect of the second constituent change manipulation on early measures of processing, despite the use of long eleven to fourteen character compounds. That study found that, for relatively long Finnish compounds, not only adults, but also second, fourth and sixth graders were processing the first constituent faster when the second constituent was preserved than in a change condition, where the second constituent was replaced by a visually similar nonword (with the first two letters preserved). However, this so-called PoF-effect was only present for compounds with a relatively high whole-word frequency, not for low-frequency compounds. To explain this pattern of results, Häikiö et al. argued that the more frequent a compound is, the more likely it is that whole-word representations make a significant contribution to the recognition process. Consequently, one may assume that in case of higher frequency compounds attention is for a longer time sustained over the whole compound, which then leads to early processing advantages for when the right second constituent is preserved.

In line with the latter study, it should be noted that effects of *whole-word frequency* are consistently observed in compound studies (e.g., Andrews et al., 2004, Pollatsek, Hyönä, & Bertram, 2000). Recent studies of Kuperman and colleagues (Kuperman et al., 2008, 2009), studying the processing of a large number of long compounds in a regression design and analysing the data with lme models, revealed that the whole compound frequency effect already appears early in processing. Tendencies for an early whole-word frequency effect were also found in previous studies (e.g., Pollatsek et al., 2000). It should be noted though that the early effects are smaller for whole-word frequency than for first constituent frequency, but the effect seems to arise somewhat earlier than the second constituent frequency effect, at least for longer compounds.

Another line of research in compound processing is on the role of segmentation cues, cues that clearly separate the first from the second constituent. In English, Juhasz, Inhoff, and Rayner (2005) studied the impact of a space on short compound processing and Häikiö, Bertram, and Hyönä (in press) and Bertram and Hyönä (2011) studied the impact of the hyphen on short and long Finnish compound processing. All these studies indicate that initial processing is much faster for easily segmentable compounds than for concatenated ones, independent of compound length. However, Juhasz et al. found that later processing was disrupted for short spaced compounds as reflected in much longer gaze durations for these compounds than for their matched concatenated counterparts. Bertram and Hyönä (2011) found the same kind of disruption for adults reading short hyphenated compounds and Häikiö et al. replicated this result for proficient elementary school children. In contrast, Bertram and Hyönä found that the hyphen facilitated long compound processing as well as Häikiö et al. found that less proficient elementary school children benefited from hyphens in reading short Finnish compounds. In order to reconcile these results, Häikiö et al. assumed that the whole-word form prominently contributes to early compound processing in case of proficient readers reading short compounds but not long compounds (for less proficient readers short compounds may be relatively long still). Inserting clear segmentation cues would make information on the whole word available later in time and by doing so disrupt the whole word recognition route, leading to overall slower compound processing. At any rate, it seems clear that the amount of information extracted from the second part of the word while fixating the first part is much smaller in case of a clear visually salient segmentation cue. The boundary study of Juhasz et al. (2009) — showing much larger preview benefits of the second constituent in case of concatenated than spaced compounds — supports this claim.

Finally, the role of semantics has been somewhat underspecified in the story outlined above, but that does not mean that eye tracking studies have neglected this aspect of compound processing. Studies directly investigating the role of semantic transparency by comparing the processing of (partially) opaque compounds (e.g., *strawberry*, *nightmare*, *deadline*) and transparent compounds (e.g., *bookcase*, *housework*) have either found no differences in any eye movement measure (Frisson et al., 2008; Pollatsek & Hyönä, 2005) or a difference in late measures only (Juhasz, 2008). Other studies that assessed the role of semantics more indirectly have also found late effects of semantics (Pollatsek et al., in press; White et al., 2008). Only Inhoff et al. (2008) report a semantic effect in FFD (stronger frequency effect for semantically dominant constituent), but it should be noted that it is unclear in how far the effect is really early here, since FFD included single fixation cases as well as first fixations of multiple fixation cases. Taken together, it is safest to conclude that — if semantic effects are detectable — they appear relatively late, reflecting that semantics gets involved at a later stage of compound processing.

It goes beyond the scope of this paper to discuss the models that have been proposed to account for this rich pattern of results (see e.g., Kuperman et al., 2008, 2009), but it clearly cannot be a simple model. What is more important in the context of this paper is that the eye movement studies cited here give us insight into the time course by which information becomes available during compound processing. As may have become clear from the above, this time course is modulated by a number of factors of which word length is perhaps the most important one.

Other eye movement studies on morphological processing

As reflected in the discussion above, most eye movement studies on morphological processing have been concerned with the processing of biconstituental compounds. However, there are a number of interesting studies that have dealt with other topics. First, four recent studies have investigated the processing of prefixed or derived words. Paterson et al. (in press) conducted a morphological priming study during sentence reading and found that only words that are morphologically and semantically related (e.g. *marsh–marshy*) prime each other. Words that are only apparently morphologically related (in that the prime is exhaustively decomposable such as in *secretary–secret*) show no such priming effects. Paterson et al. (in press) included the prime-/control-target pairs in declarative sentences with 2 to 3 intervening words ('*The forest had a marshy/thorny path leading to a* *marsh where students studied wildlife*'), while registering readers' eye movements. The results are in line with the results of an unmasked priming experiment of Rastle, Davis, and New (2004) and in line with their hypothesis that a later stage of suffixed word processing involves semantics. In addition, however, Paterson et al. found evidence in post-target reading times (word following target word, here *where*) that an apparent morphological relationship (secretary–secret) is reinstated in case of a processing difficulty caused by an initial misidentification of a word.

Niswander-Klement and Pollatsek (2006) did a study using English prefixed words, manipulating root morpheme frequency and whole word frequency as well as word length. They found significant root morpheme frequency effects for longer prefixed words (8.5 characters on average), but not for shorter prefixed words (6.5 characters). In contrast, there was a whole-word frequency effect for shorter prefixed words but not for longer prefixed words. Root frequency effects (as well as a 100 ms novelty effect) were also obtained in Pollatsek, Slattery, and Juhasz (2008) for both existing and novel English prefixed words. Finally, Kuperman, Bertram, and Baayen (2010) conducted a large regression study on Dutch suffixed words embedded in sentential contexts. Their main finding was that the use of whole-word information in processing depends on the length of the suffix (with a larger contribution once the suffix was short). Taken together, the eye movement studies confirm findings of earlier lexical decision studies (e.g., Ford, Davis, & Marslen-Wilson, 2010; Laudanna & Burani, 1995) that root and affix properties modulate the role of morphological constituents.

There are also a couple of eye movement studies that deal with trimorphemic words. Pollatsek, Drieghe, Stockall, and de Almeida (2010) studied the processing of structurally and semantically ambiguous words such as *unlockable*, which either can be interpreted as *un-lockable* (cannot be locked) or *unlock-able* (can be unlocked). They found that readers have a clear preference for left-branching structures (*unlock-able*), but note that this preference most likely is driven by the generally higher frequency of the C1C2-combination (*unlock*) in comparison to the C2C3-frequency (*lockable*). Bertram, Kuperman, Baayen, and Hyönä (2011) studied the effect of inserting a hyphen at constituent boundaries in triconstituent Dutch compounds like *voetbalbond* 'football association' and triconstituent Finnish compounds like *lentokenttätaksi* 'airport taxi'. The insertion of hyphens is not in line with Dutch and Finnish spelling conventions, but Bertram et al. nevertheless showed that when hyphens are inserted at major constituent boundaries (*voetbal-bond; lentokenttä-taksi*), readers are much faster on the first part of the word (*voetbal*, *lentokenttä*) than when they are not. Moreover, the study showed that in the latter part of the experiments Dutch hyphenated compounds were read equally fast and Finnish hyphenated compounds even faster than their concatenated counterparts, despite the spelling illegality.

A final series of studies concerns the role of agreement in Finnish inflected nouns. In Finnish modifiers agree with their head nouns in case and in number, which is expressed by means of suffixes (e.g., *vanha/ssa talo/ssa* 'old/in house/in' => in the old house). Vainio, Hyönä, and Pajunen (2003, 2008) showed processing benefits for this kind of agreement, but the effects appeared relatively late. That is, they found that the word following the target noun *talo/ssa* was read faster when it was preceded by an agreeing modifier (*vanha/ssa*) than when no modifier was present. Vainio et al. (2003, 2008) concluded that agreement exerts its effect at a later stage, namely at the level of syntactic integration and not at the level of lexical access. However, the modifiers and head nouns employed were relatively short (seven or eight characters). Vainio, Bertram, Pajunen, and Hyönä (2011) thus investigated whether the same kind of effects can be found when head nouns are considerably longer (e.g., *kaupungin/talo/ssa* 'city house-in' => in the city hall). Their results showed again a facilitative agreement effect, but — in contrast to what was found for shorter words — the effect not only appeared late, but was also observed in earlier processing measures. They concluded that in processing long words benefits related to modifier-head agreement are not only constricted to post-lexical syntactic integration processes, but extend to lexical identification of the head noun as well.

Final remarks

In this paper, I have tried to argue that there are several advantages in using eye tracking while assessing the role of morphology in processing complex words. In addition, I have explained how to conduct and analyze normal eye movement experiments as well as experiments using the boundary technique. The review on eye movement studies since 2005 has mainly focused on compound processing and the temporal unfolding of information while processing them. However, I have also outlined a number of other eye movement studies that have shown other interesting aspects of complex word processing. I hope that the current paper has exposed the potential of eye movement research and that it will pave the way for more eye movement research on morphological processing in the near future.

Notes

1. The authors note that words recognized via this route are not necessarily accessed as whole-word visual templates. That is, they assume that this route also includes letter and probably letter cluster detection. However, this route does not include the activation of morphological units.

2. The DPI eyetracker has been for a long time topping the list in terms of spatial and temporal resolution, but other eye trackers like SMI and SR-Research's Eyelink have caught up, especially when it comes to temporal resolution.

3. There is no complete consensus as to what should be considered as short-lasting; sometimes fixations lasting less than 50 ms, sometimes less than 80 ms and sometimes less than 100 ms are taken to be short-lasting. Since there are very few fixations that last between 50 and 100 ms, there will not be much difference in applying either of these upper boundaries.

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