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Language Processing in Reading and Speech Perception is Fast and Incremental: Implications for Event Related Potential Research

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Abstract

An overview of language processing during reading and listening is provided. Evidence is reviewed indicating that language processing in both domains is fast and incremental. We also discuss some aspects of normal reading and listening that are often obscured in event related potential (ERP) research. We also discuss some apparent limitations of ERP techniques, as well as some recent indications that EEG measures can be used to probe how lexical knowledge and lexical or structural expectations can contribute to the incremental process of language comprehension.

Language is one of the greatest assets humans possess. It is a highly polished skill, and it enables us to communicate freely with others and express and examine our thoughts and ideas. Understanding language processing should be of paramount interest to psychologists. For much of its history, psychology ignored how language works, but in the past 40 years research on language processing has thrived, and much has been learned about various aspects of language, ranging from word identification and lexical access to sentence processing to discourse comprehension. In this article, we will argue that language processing is fast and largely incremental, in the sense that substantial syntactic, semantic, and pragmatic processing of a word is done while the eyes are fixated on that word or while that word is being heard. We examine some new ways of probing the early stages of language comprehension

We will first describe some basic characteristics of reading and listening and discuss their similarities and differences. Our goal is to provide a very general background for the articles in the present volume, which use event-related potentials (ERP) or other measures of electroencephalographic (EEG) activity to study brain functioning during language processing. Before briefly commenting on the contributions of these articles, we will discuss some apparent limitations of these techniques, as well as some recent indications that EEG measures can be used to probe how lexical knowledge and lexical or structural expectations can contribute to the incremental process of language comprehension.

We think it is important to note that reading and speech, while sharing some similarities, are also fundamentally different in some important ways. First, it is well-known (Rayner, Foorman,

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Perfetti, Pesetsky, & Seidenberg, 2001) that speech typically emerges quite naturally with virtually all toddlers learning to speak without any formal instruction, whereas reading typically requires some specific instruction via teachers for children to begin gaining the rudimentary skills involved. Second, while speech occurs in a serial incremental fashion and listeners have little or no information about what word n+1 will be until after word n is heard, there are some parallel processing components of reading: multiple letters of a word seem to be processed at once, and parafoveal preview provides some information about words that have not yet been fixated (see Rayner, 1998). Third, speech is in some sense fleeting, as once the words have been uttered listeners can't go back and replay the speech signal. On the other hand, readers normally have the option of looking back in text at words they have previously processed. Finally, speech provides prosodic information that is lacking on the printed page. It is sometimes argued that reading is speech made visible, but it should be obvious that there are enough unique properties of reading and speech that this assertion does not hold.

Reading and Listening: Basic Properties

Reading

During reading, the visual properties of the text are encoded via a series of eye movements (Rayner, 1998), generally from left-to-right across the line of text. The visual information is encoded during *fixations*, which typically last about 200-250 ms (though the range is from 50 ms to over 500 ms). The movements of the eyes between the fixations, *saccades*, typically last 20-30 ms; no new information is obtained during these movements. Indeed, vision is suppressed during saccades (Matin, 1974). On average, the eyes move 7-8 letter spaces (though the range is from a single letter space to over 20 spaces) for readers of English and other alphabetic writing systems; letter spaces, rather than visual angle, are the appropriate measure for indexing how far the eyes move during reading (Morrison & Rayner, 1981). On about 10-15% of the saccades, *regressions*, readers move their eyes backwards in the text to look at material that has received some prior processing. As text difficulty increases, readers tend to increase fixation durations, decrease saccade size, and increase regressions.

The reason readers need to make eye movements during reading is very much related to the anatomy of the retina. The ability to discriminate the fine details needed to know that one letter is an *e* and another is an *o* or *c*, or that a word is *check* rather than *cheek* or *chest* rather than *chart*, requires eye movements that bring relevant parts of the text into foveal vision. Outside of the fovea (which extends 1 degree on either side of the fixation point), acuity drops off rapidly in parafoveal vision (extending to 5 degrees) and even more so in the peripheral retina. A great deal of research on the perceptual span (or region of effective vision during an eye fixation) has revealed that skilled readers of English (and other alphabetic writing systems) typically acquire information from a region extending from 3-4 letter spaces to the left of fixation to about 14-15 letter spaces to the right of fixation (Rayner, 1998). Within the perceptual span, different types of information are acquired: information used to identify words is obtained from the region 3-4 letters left of fixation up to 7-8 letter spaces to the right of fixation. Beyond that, more gross types of information (beginning letters of the next word unidentified word, letter feature information, and word length) are obtained. Questions about the nature of the perceptual span have been answered via the use of the gaze-contingent moving window paradigm (McConkie & Rayner, 1975; Rayner & Bertera, 1979) in which the amount of useful information that readers have available on any fixation is controlled.

Research (see Rayner, 1998) has also documented that readers get preview benefit from words to the right of fixation that they have not yet identified. The preview benefit effect has been documented via another gaze-contingent paradigm, called the boundary technique (Rayner, 1975), in which display changes are made during a saccade as readers move their eyes from word n to word n+1. Thus, if readers have a valid preview (as compared to an invalid preview) of word n+1, they will fixate on it for less time when they move their eyes from word n to that word.

In addition to the perceptual span and preview benefit results, another highly robust effect in reading is that properties of the fixated word influence how long readers look at a word. Specifically, readers fixate longer on low frequency words than high frequency words (Inhoff & Rayner, 1986; Rayner & Duffy, 1986) and on unpredictable words than predictable words (Ehrlich & Rayner, 1981; Rayner & Well, 1986). They are also more likely to skip (not directly fixate on) predictable words than unpredictable words[1]. Even though readers skip some words, it doesn't mean that the word isn't processed; it is processed in the fixation prior to the skip. While fixation times on words vary as a function of factors such as frequency and predictability, it is also important to point that there are spillover effects. Thus, even though frequency effects are apparent on the fixation time on a given word, they can also spillover onto the next word (Rayner & Duffy, 1986), suggesting that some aspects of processing a word take place only after the eyes have moved on to the next word or that some pre-processing of a not-yet-fixated word can occur while the eyes are still on the previous word.

All of the points that we have discussed add up to a situation in which readers are rapidly identifying words during reading, with lexical access typically completing while the word is fixated. The values we discussed above with respect to eye movement characteristics lead to skilled readers typically reading at rates between 250-350 words per minute (wpm). Thus, language processing during reading is relatively fast.

The fact that eye movements reflect moment-to-moment language processing has led to them being widely used to investigate issues such as sentence processing (and lexical and syntactic ambiguity resolution). How long readers look at individual words and how long they look at words or phrases as they deal with the ambiguities that are prevalent in language clearly reveal some important information about the nature of language processing. Not only do word frequency and word predictability influence fixation times on given target words, other word level variables such as age-of-acquisition (Juhasz & Rayner, 2003, 2005) and plausibility of a word (Rayner, Warren, Juhasz, & Liversedge, 2004) also influence how long readers look at a word. Other factors such as clause and sentence wrap-up (Rayner, Kambe, & Duffy, 2000) and pronominal reference (Ehrlich & Rayner, 1983) exert relatively immediate effects on eye movements. Starting with an influential article by Frazier and Rayner (1982), there have been numerous studies using eye movements to examine sentence processing and the resolution of lexical ambiguity. And, other forms of ambiguity have also been investigated via eye movement data. Although there are some questions about when given variables have an effect, it seems fairly safe to conclude that the immediate movements of the eyes through text is largely driven by lexical properties of words, and that other higher order influences generally have later effects (Clifton, Staub, & Rayner, 2007; Staub & Rayner, 2007).

The large database that has accumulated concerning reading has led to the development of a number of computational models of eye movement control during reading. The most prominent models are the E-Z Reader model (Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatesk, Fisher & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003), SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005), and Glenmore (Reilly & Radach, 2006). In general, these models (and other models) differ in terms of how early cognitive processes exert an influence on eye behavior and the extent to which lexical processing is serial (so that word n is not processed until word n-1 has been processed) or parallel (so that there is simultaneously lexical activation for word n and word n+1, and even word n+2, as well as continued processing of word n-1).

[1]Readers are also more likely to skip high frequency words than low frequency words, but this effect isn't as strong as the predictability effect on skipping.

Obviously, our bias is that lexical processing is serial in reading as well as in listening. Although some have argued that a substantial portion of lexical processing is done in parallel, so that words previously fixated as well as words yet to be fixated are processed at the same time as the fixated word (Engbert et al., 2005) we believe that the evidence we have reviewed here and elsewhere (Rayner, 1998; Reichle et al., 2003) provides strong evidence that reading is fast, incremental, and largely serial.

Listening

The acoustic speech signal provides a nearly-continuous stream of spectral information about what the speaker's mouth is doing (and indirectly, about the speaker's intentions). The signal is broken by brief periods of silence that correspond to closures of the mouth (during stop consonants) and not generally to breaks between words. A great deal is known about how the acoustic properties of the speech waveform are mapped into the perception of phonological segments and about the recognition of spoken words (see Cutler & Clifton, 1999; Dahan & Magnuson, 2006; McQueen & Cutler, 2001, for overviews).

The recognition of words in normal speech has to take place quickly and efficiently. Estimates of normal speaking rate range from 120 to 200 words per minute, or 120 to 600 syllables, or in some estimates, as many as 20 to 30 segments per second (Crystal & House, 1990; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). Experiments on compressed speech suggest that comprehension can be successful at two times or more the normal rate (e.g., Dupoux & Green, 1997). Thus, while perception of spoken speech is somewhat slower than a skilled reader's normal reading rate (250 to 350 words per minute), the former approaches the latter in speed.

One of the important tasks for a listener is to segment the continuous speech stream into words. While there are some signals to word beginnings in the speech stream (e.g., some constraints on sequences of phonological segments that can occur inside a word, and in some languages including English, at least a statistical tendency for words to begin with stressed syllables; cf. Cutler, Danan & Van Donsellar, 1997), much of the work of segmentation must be based on knowledge of the words that exist in a language. A listener is generally able to take a string of segments that could be broken at different points into possible words, and parse it into a coherent string of words in which every segment is assigned to a word (e.g., *first acre* does not result in the perception of *steak* even though that string of segments is included in the utterance). The listener seems to be able to recognize the end of one word and prepare for the beginning of the next, a process that seems to result in peaks of attention at word beginnings (Sanders & Neville, 2003).

The recognition of a spoken word has a substantial serial component to it, as modeled in the cohort model of speech perception and its descendants (Marslen-Wilson, 1987, 1990; Marslen-Wilson & Welsh, 1978; McClelland & Elman, 1986; Norris, 1994). A first-pass description of auditory word recognition would claim that all words that are consistent with the beginning phonetic segments of a word are first activated, and then this initial cohort is narrowed down as new segments are heard. This description is incomplete. Words that do not begin with the initial segments that are heard but that have other similarities (e.g., rhymes) can compete. Further, substantial parallel processing of successive segments occurs, reflecting how the pronunciation of one segment influences the pronunciation of surrounding segments (Marslen-Wilson & Warren, 1994). Such coarticulation enables parallel processing of multiple segments, facilitating perception of the rapidly-arriving speech stream.

The speed of recognizing a word is not determined entirely by its phonetic makeup. It is affected as well by the frequency of occurrence of the word in the language and by its predictability and coherence in context, and to the extent that auditory stream segmentation is driven by the

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recognition of the words in the stream, these factors could affect how a stream is segmented. But just as is the case in reading, comprehension of spoken language does not end with recognizing words. Just as in the case of reading, the question arises, how incremental is the process of comprehending speech?

Although on-line research on sentence comprehension has proven to be more difficult with listening than with reading, the existing evidence indicates that listeners recognize words and parse and comprehend speech in a nearly-incremental fashion. Recent research in the “visual world” paradigm, in which a listener’s eye movements to potential referents are measured while hearing speech, has indicated that words are recognized as denoting potential referents in the visual scene essentially as quickly as the auditory information arrives (Allopena, Magnuson, & Tanenhaus, 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) and even that coarticulation and prosodic information is used early in the process of recognizing words (e.g., Dahan & Gaskell, 2007). The same paradigm suggests that comprehension, as reflected in eye movements, is sensitive very quickly to the syntactic possibilities afforded by the speech stream as constrained by the referential context (Spivey, Tanenhaus, Eberhard, & Sedivy, 2002) and even that listeners can anticipate upcoming referents (Altmann & Kamide, 1999). There is thus substantial data that listening, like reading, is fast, incremental, and largely serial. As will be discussed later, ERP research can be expected to contribute to our understanding of the on-line nature of speech comprehension.

Implications of Speed and Incrementality for ERP Research

In the preceding section, we noted that reading is relatively fast (on the order of 250-350 wpm for most skilled readers), and listening can approach but probably not reach this rate. The rapid rate of word recognition and comprehension leads to a troubling issue with respect to ERP research. Most ERP studies of language have focused on later components of the waveform, such as the N400 (a negative-going wave occurring about 400 ms after stimulus onset). Most of the research on the N400 has concentrated on how it is sensitive to the semantic relationships among words (cf. Kutas, Van Petten, & Kluender, 2006; but cf. Bornkessel, McElree, Schlsewski, & Friederici, 2004, for evidence that it is also sensitive to syntactic factors). However, since factors that reflect the identification of individual words, including frequency and predictability affect the N400 (e.g., Dambacher & Kliegl, 2007), it is sometimes taken as an index of word recognition.

As discussed earlier, in normal reading eye movements seem to be largely controlled by processes of recognizing the words in the text, and seem typically to occur less than 300 ms after fixating a word (and, given the latency of eye movements, estimated to be 150 ms or more, must be programmed even more quickly). Words must be recognized very quickly. If listening is essentially incremental, a similar conclusion is apparent. A listener must identify words essentially as they appear, up to 3 or so a second, and potentially even more quickly if recognizing one word is required for a listener to prepare for and identify the beginning of the next word. A challenge for ERP research is the apparent discrepancy between what a normal reading rate dictates in terms of speed of lexical processing and what the ERP record has mainly shown (Sereno & Rayner, 2003; Sereno, Rayner, & Posner, 1998). That is, many significant ERP differences (such as those due to word frequency and word predictability) seem to occur too late given eye movement data and the estimated rate of spoken language comprehension. In reading, for example, by the time an N400 has reached its peak, the eyes have already moved off of the target word and on to the next word (cf. Dambacher & Kliegl, 2007). It should be noted that the N400 response may begin substantially before its peak, but because of variability in the EEG signal, the onset of an N400 is difficult to identify, making it a less-than-satisfactory indicator of word recognition.

Consider the effects of word frequency and word predictability in reading. These effects typically show up on the word whose frequency or predictability is manipulated, with the fixation time measures being on the order of 250-300 ms. But the effect of a given lexical manipulation (like frequency) seems to be occurring too late in the ERP record if it shows up in the N400. This leads to an interesting conundrum: how can the eyes be faster than the brain?

We offer three possible explanations for why this conundrum exists. First, to avoid the electrical response to one word appearing during the presentation of the next word, ERP research typically presents words one at a time (via rapid serial visual presentation, RSVP) at the rate of about 400-500 ms or longer per word. This rate is much slower than readers typically process words in normal reading. Thus, part of the reason why lexical effects typically show up later in ERP than eye movement research may well have to do with the rate of presentation of the words. Second, in addition to using relatively slow rates of presentation, RSVP reading denies readers any type of preview benefit for upcoming words that is typical of reading. This probably also contributes to differences between eye movement and ERP studies in terms of how early in the record certain effects appear. Third, it may simply be the case that early ERP researchers haven't looked in the best way to identify earlier occurring effects in the waveform. As noted by Penolazzi, Hauk, and Pulvermüller (2007), while the N400 is long-lasting and topographically widespread, and easily identified, earlier components may be more focal and shorter, and harder to identify given temporal and spatial variability in the EEG. Some recent research, including articles in this special issue, has begun to examine earlier components of the waveform, using techniques that reduce variability across trials as well as techniques that accumulate data across dense electrode arrays, with emerging indications of early effects (Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Maurer & McCandliss, 2008; Nobre & McCarthy, 1994; Penolazzi et al., 2007; Sereno, Brewer, & O'Donnell, 2003; Sereno, Rayner, & Posner, 1998).

Let us consider each of these three issues. Concerning the first (slow presentation rate), there has been some recent progress. Research in which the rate of presentation was much closer to normal reading (200 to 250 ms per word) yielded evidence of early appearing word frequency and word predictability effects in the ERP record (Dimigen, Sommer, Dambacher, & Kliegl, 2007). To be sure, this approach has technical problems, e.g., the difficulty of separating out late-appearing responses to one word from the early responses to the next word, and further, the components that have been examined in the available research are still too slow to directly reflect processes that index word recognition and eye movement control. Still, in our view, such a procedure, in which the rate of presentation is made much more like normal reading, is a more promising solution than comparing ERP measures to self-paced reading (Ditman, Holcomb, & Kuperberg, 2007) since self-paced reading often involves slow rates of processing (400 ms per word or longer). Concentrating more on spoken language also has promise, since while spoken language does not typically reach the rate of normal skilled reading, it approaches that rate more closely than either traditional word-by-word presentation or self-paced reading, and doesn't add novel and potentially disruptive task demands to the familiar processes of comprehending written or spoken language. Finally, some researchers have used the same materials across experiments (Ashby & Martin, 2008; Dambacher & Kliegl, 2007; Raney & Rayner, 1993; Sereno et al., 1998) in which eye movements were recorded for one group of subjects while ERPs were measured for another group of subjects. Here, researchers can look for convergence and divergence across the two measures.

An even more promising approach than speeding presentation allows a reader to see text in a normal fashion while simultaneously measuring eye movements and ERPs. Besides permitting normal reading skills to be used, this procedure allows the reader to make use of parafoveal preview of not-yet-fixated words. The potential importance of such preview in interpreting the place of ERP responses in the time-line of processing was discussed by Sereno et al. (1998), who argued that taking into account the absence of parafoveal preview in most ERP research could yield greater consistency between eye movement and ERP measures. Allowing parafoveal preview during normal reading and indexing scalp electrical activity to fixations on particular words could simultaneously address the questions about slow rate of word presentation and absence of parafoveal preview. Language researchers have avoided the technique, largely because it presents serious technical problems. Some problems reflect the possibility of electrical contamination of the ERP record by the eyetracking equipment, but modern equipment seems to have minimized this problem. A less tractable problem stems from the fact that the moving eyes act as electrical dipoles, creating substantial electrical noise that contaminates the EEG record.

Two ways of addressing this latter problem have appeared. The first, exemplified by Dimigen, Sommer, Dambacher, and Kliegl (2007), uses statistical regression procedures to subtract the estimated effect of eye movements from the EEG record. In principle, this could provide uncontaminated ERPs during normal reading, but researchers are cautious because the statistical adjustments require assumptions that are difficult or impossible to evaluate in any single study. The second approach, exemplified by Reichle, Tokowicz, Liu, and Perfetti (2008), examines scalp electrical activity in the period of time immediately *before* the start of a saccade. This is the time period during which eye movements are programmed, and could in principle exhibit important brain activity involved in recognizing words and moving the eyes, and since it occurs while the eyes are stable, it is not contaminated by eye movements. This approach relies on using an experimental task in which there are no eye movements during the ERP analysis window, which largely rules out the possibility of looking at electrical activity in the brief periods between saccades in normal reading. We suspect that both approaches will pay off handsomely in the long run, but that they will require the coordinated efforts of researchers examining sentence processing and scalp electrical activity at many different levels.

Contributions in the Present Special Issue

The papers in the current issue address the preceding concerns in various ways, direct and indirect. Together, they show the progress contemporary ERP research is making in probing the early time course of recognizing words. Some of the papers provide additional evidence for the existence of early ERP components in the recognition of written words, components that occur early enough to be reflecting cognitive processes that occur during the process of word recognition. These papers extend the evidence for early components in various interesting ways. For instance, Ashby, Sanders, and Kingston show that phonological features such as length or voicing play an early role in recognizing written words. Segalowitz and Zheng's data indicate that semantic effects can appear in the first 170 ms of recognizing a word, and Spironelli and Angrilli examine age differences in the automaticity of early components. Scott, O'Donnell, Leuthold, and Sereno present additional data about very early components of the response to words and examine how they are affected by the emotional tone of words, and Kissler, Herbert, Winkler, and Junghofer examine further ERP effects linked to the emotional content of words. Catena, Houghton, Valdes-Control and Fuentes provide a way to identify early components of the response to a primed word, uncontaminated by the late-appearing effects of the masked prime, and Hauk, Pulvermüller, and Marslen-Wilson present a novel way of analyzing scalp electrical activity in the period about 100 ms after written word onset.

Several papers examine early activity in response to spoken words. Astheimer and Sanders extend previous work examining shifts in attention that occur as one word is recognized and the listener prepares for the next word. Newman and Connolly report on early response to an unexpected initial phoneme of a spoken word, and Friedrich and Schild provide evidence for an early response to a speech sound that mismatches a primed sound, together with a later negativity when an initial syllable mismatches a prime. Tan and Molfese show that preschool age children show early responsiveness to the mismatch between a visual scene and spoken verbs and nouns. Finally, Proverbio, Adorni, and Zani, and Midgley, Holcomb, and Grainger examine phonolological and semantic processing (respectively) in the first and second languages of bilinguals, mapping out the levels of facility and automaticity in L1 and L2.

The papers in this collection thus admirably address one of our responses to the conundrum we posed, how the eyes can be faster than the brain. They show that clever, incisive experiments can uncover EEG activity that reflects very early visual, phonological, and semantic processing of words, and they begin to shed light on the functional significance of some of this activity. They raise fascinating questions about, for instance, how attention might be reflected in the EEG record during reading as well as during listening, how the EEG record might reflect phonological processing of written as well as spoken language, and how semantic properties of words might affect the early stages of recognizing words. They give substantial promise of shedding light on just how words can be recognized quickly enough to control eye movements in reading and the segmentation of a speech stream into individual words. They also set the stage for a new round of research, examining how words, once they are recognized, can be put together into comprehended phrases and sentences, and they suggest that the field is ready for future technological advances that permit the study of language as it perceived in normal reading and listening conditions.

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