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Eyetracking Methodology: A User's Guide for Linguistic Research

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Abstract

During the past decade, the use of behavioral (e.g. picture/word naming, self-paced reading, eyetracking) and electrophysiological (e.g. event-related potentials) quantitative experimental techniques historically associated with psychology has flourished in linguistics. These techniques are shaping linguistic theories in new ways and it is important to understand how they can contribute to our field. This article focuses on the use of eyetracking, a research methodology that measures eye positions and movements through a device called an eyetracker. In linguistics, eyetracking is generally employed for studying language processing during comprehension and production. The paper is organized as follows. Section 1 presents the benefits of eyetracking for linguistic research. Section 2 explains terminology commonly used in eyetracking studies and discusses issues relevant for stimuli creation and data analysis. Section 3 compares the eyetracker models employed in linguistic studies and provides useful links to obtain further information. Finally, Section 4 summarizes representative eyetracking research on Spanish and Portuguese.

1. Benefits of eyetracking for linguistic research

While methods for studying language processing during comprehension and production abound, eyetracking methodology offers unique advantages for linguistic research. Self-paced reading, rapid serial visual presentation (RSVP), and lexical decision tasks are unnatural in that they elicit atypical rates of reading either by disrupting the flow of reading or requiring the addition of a secondary task. Rayner & Sereno (1994) argued that the behavior of participants in eye-movement experiments is quite natural. Unlike other techniques, there are no disruptions, and participants can regress to previously read material. Altarriba, Kroll, Sholl & Rayner (1996) advised using eyetracking instead of RSVP because the former did not require any decision-making strategies and took less time (see Hyönä, Laine & Niemi 1995, for similar findings when comparing eyetracking and standard versions of naming and lexical decisions tasks).

In addition to being preferable for word naming and lexical decision studies, eyetracking is also recommended for sentence processing. Prior to eyetracking, self-paced reading was the most popular method for studying language processing. However, self-paced reading only reflects initial parsing decisions based on total reading time of a given segment without regressions, whereas eyetracking offers a complete picture of sentence processing by including second pass fixations and regressions. In their eyetracking task, Altarriba et al. (1996) found significant results based on skipping probability and first-fixation times – ne neither of which are available in this technique – and noted that they would have come to very different conclusions if they had employed self-paced reading. Similarly, Frenck-Mestre & Pynte (1997) reported greater sensitivity to verb constraints in nonnative than native readers, a finding that would not have been apparent without the use of eyetracking. In the same line, Papadopoulou & Clahsen (2003) reported long reading times for disambiguating words in their self-paced reading stimuli; however, because both analysis and reanalysis are included in self-paced reading times, any clear-cut claims about readers' initial parsing preferences are untenable. Finally, Wilson & Garnsey (2009) used both self-paced reading and eyetracking tasks, and concluded that eyetracking's early processing data absent in self-paced reading were what provided more robust evidence of verb-bias influence on structure building. This evidence would not have been found without the use of eyetracking, which allows for the fine-grain analysis of reading patterns, both regressions and regression reading times. Dussias (2010) notes that eyetracking allows researchers to address more subtle questions in linguistics, such as whether learners apply phrase-structure-based parsing principles in their L2, or how bilinguals judge licit and illicit code-switches to determine the existence of acceptable and unacceptable switching boundaries (Dussias 2003).

More recently, linguistic research has also benefited from the incorporation of aural processing and the visual world paradigm into eyetracking (Tanenhaus 2007). Visual world paradigm studies ask participants to respond to aural instructions or produce utterances related to real world objects or pictures in a display while their eye movements are recorded. Because this technique allows a "real-time interdependence between spoken language processing and visual perception" (Richardson & Spivey 2004, p.14), it has been used to examine sentence processing during comprehension and production (e.g. Brown-Schmidt, Campana & Tanenhaus 2005, McMurray, Tanenhaus & Aslin 2002, Sagarra, Ellis & Gauthier 2011, Seibert Hanson & Sagarra 2011, Spivey, Tanenhaus, Eberhard & Sedivy 2002 and Trueswell, Sekerina, Hill & Logrip 1999) and L2 lexical activation (e.g. Canseco-Gonzalez, Brick, Fischer & Wagner 2005, Ju & Luce 2004 and Spivey & Marian 1999).

Because eye movement data are sensitive and implicit, they can be used with simple natural tasks like picking up and moving objects, which make it appropriate for linguistic studies involving young children. The use of eyetracking with children

has helped addressed a myriad of questions: from syntactic ambiguity resolution in real time (Trueswell et al. 1999) to strengths and weaknesses of young readers in order to develop individualized education plans for delayed readers (Evans & Saint-Aubin 2005). However, Lew-Williams & Fernald (2010) point out that working with children adds another dimension in that maintaining fixation on a central point is challenging for children, and recommend the use of specific eyetracking techniques such as the looking-while-listening technique.

To summarize, eyetracking is superior to self-paced reading because it includes second pass reading fixations and regressions, and it has been used in linguistic research to examine language processing during comprehension and production in children and adults. Next, we discuss common terms used in eyetracking literature and issues researchers need to keep in mind when designing and interpreting an eyetracking study.

2. Eyetracking terminology and measures

Before designing a study, it is important to understand the terminology and technical aspects of eyetracking. Eyes do not stream smoothly across a text during reading; instead, they fixate on a particular region for about 200-250 ms, jump ahead (*saccade forward*) about eight character spaces, and regress to previous words (Rayner & Sereno 1994). There are numerous studies that have investigated why we move our eyes where and when we move them (see Rayner, Reichle & Pollatsek 1998 for an overview). This strand of research has generated fruitful insights, providing robust evidence that "when eye movements are recorded during reading, there are systematic relations between fixation durations and the characteristics of the fixated words" (Dussias 2010, p.150, Ehrlich & Rayner 1981, Just & Carpenter 1980 and Rayner 1978, 1983). Linguists can also benefit from this line of research for stimuli creation and data interpretation. For example, we know that short words (three letters or less) are more likely to be skipped than long words (eight letters or longer) (Brysbaert & Vitu 1998 and Rayner & McConkie 1976), that function words (e.g. prepositions, determiners) are fixated less than content words (e.g. nouns, verbs, adjectives, adverbs) (38 and 83% of the time, respectively), and that some readers can process more information than others from a single fixation (*perceptual span*).

The term *perceptual span* refers to the vertical and horizontal span (3-4 character spaces, Rayner 1975) within which eyes have sharp enough vision to process text. The perceptual span expands asymmetrically depending on the language: to the right of the fixation for readers of English, to the left of the fixation for readers of Hebrew (written right to left), and rotated for readers of Japanese (written vertically) (Osaka & Oda 1991 and Rayner & Sereno 1994). Researchers should be aware of two effects related to the perceptual span: the *parafoveal preview effect* (the processing associated with a particular word happens on the prior

fixation) and the *spillover effect* (the processing of a difficult or low frequency word that spills over onto the processing of the following word) (Rayner & Duffy 1986). When both effects occur, it is more difficult to determine which fixation times are reliable measures of processing, and therefore it is crucial to control the context in which target words appear. Moreover, Frenck-Mestre (2005) suggests that the region of interest does not appear at the beginning or the end of a sentence or a line break because readers tend to skip these regions and they can show "wrap-up effects" (i.e. additional time spent on sentence-final words to understand the entire sentence, Just & Carpenter 1980). This explains why Carreiras & Clifton (1999) added extra information at the beginning and at the end of their sentences containing relative clauses to adapt the stimuli from self-paced reading to eyetracking. Finally, Frenck-Mestre recommends that researchers control for "low-level" factors such as the physical properties of words and the ocular-motor system itself and "high level" linguistic factors such as lexical frequency and predictability of a following word when creating their stimuli for eyetracking studies.

Eyetracking generates vast amounts of data but the measures most commonly used in studies on reading comprehension are first fixation durations, gaze durations, and total time. *First fixation durations* are used to measure lexical access and additional fixations reflect higher-order processing (Inhoff 1984), but some researchers argue that the second fixation is more revealing of lexical access (e.g. O'Regan 1990). However, it is not clear what constitutes a fixation: some researchers exclude fixations longer than 1000ms and shorter than 100ms (Kambe, Rayner & Duffy 2001), others exclude fixations longer than 800ms and shorter than 80 ms (Betancort, Carreiras & Sturt 2009), and still others exclude fixations longer than 1000ms and shorter than 120ms (Folk & Morris 2003). *Gaze duration* is the sum of all consecutive fixations on a word before leaving the region of interest (Just & Carpenter 1980). For words that are skipped, researchers may choose to score this based on fixations in the region to the left of the target word (within three characters). Finally, *total fixation time* consists of the sum of the gaze duration and the fixation time of all regressions made to the critical region.

In all, researchers should avoid the spillover and parafoveal preview effects as well as have the interest region at the beginning or end of a sentence or a line break. Also, they should include as much information as possible in their analysis, including first fixation durations, gaze durations, and total time. Section 3 outlines the most popular eyetrackers currently used for language research.

3. Eyetracker systems and models

Before purchasing an eyetracker, it is important to take into consideration the brand and the model depending on the type of research to be conducted. For example, while head-mounted eyetrackers that allow more freedom of movement are fine for shorter experiments with adult subjects, they are preferable for children, and desk-

mounted eyetrackers with a chinrest or bite bar are better for longer experiments for adults. While the most popular models are not particularly portable or durable, newer models are being produced that are lighter and more mobile without much loss of accuracy or resolution. Still, the average cost for an eyetracker is rather high, and it is therefore important to choose the model that best fits a laboratory's research needs.

Of the various eyetrackers on the market, there are six basic models that have been used most extensively in language research. The most prominent head-mounted eyetrackers are:

- ***EyeLink I and II*** (e.g. used in Dussias 2003, Dussias & Sagarra 2007, Ellis & Sagarra 2010, Keating 2009, McMurray, Tanenhaus & Aslin 2002 and Salverda & Tanenhaus 2010)
- ***ASL E4000*** (e.g. used in Allopenna, Magnuson & Tanenhaus 1998, Brown-Schmidt & Tanenhaus 2006, Dahan, Swingley, Tanenhaus & Magnuson 2000, Eberhard, Spivey-Knowlton, Sedivy & Tanenhaus 1995, Hyönä, Laine & Nieme 1995 and Salverda, Dahan, Tanenhaus, Crosswhite, Masharov & McDonough 2007).
- ***ISCAN ETL-500*** (e.g. used in Kaushanskaya & Marian 2007, Spivey & Marian 1999 and Trueswell et al. 1999).

The most popular desk-mounted or remote versions are:

- ***EyeLink 1000/2000*** (e.g. LaBrozzi 2009, Ellis & Sagarra 2010, Seibert Hanson & Sagarra 2010, Van Assche, Drieghe, Duyck, Welvaert & Hartsuiker 2011).
- ***Tobii*** (e.g. Ogusuko, Lukasova & Coutinho de Macedo 2008, Hendriks, Banga, Van Rij, Cannizzaro & Hoeks 2009 and Trueswell & Papafragou in press).
- ***SRI Dual Purkinje*** (e.g. Altarriba et al. 1996, Betancort, Carreiras & Sturt 2009, Carreiras & Clifton 1999, Kambe, Rayner & Duffy 2001, Meseguer, Acuña-Fariña & Carreiras 2009 and Wilson & Garnsey 2009).
- ***ISCAN ETL-500*** (e.g. Papafragou, Hulbert & Trueswell 2008, Patson & Ferreira 2009 and Sekerina & Brooks 2007).

Typically each model comes with its own data recording and analysis software, and many models are Microsoft Office, E-Prime, and ERP and fMRI compatible. Additional information about each brand (such as accuracy specifications and pricing) can be found on the manufacturers' websites: ASL (http://asleyetracking.com/site/), Dual Purkinje (http://www.fourward.com/), EyeLink (http://www.sr-research.com/index.html), ISCAN (http://www.iscaninc.com/), and Tobii (http://www.tobii.com/).

Up to now, we have discussed why eyetracking is beneficial for linguistic research, and we have presented what conceptual and technical issues researchers should keep in mind when designing or interpreting eyetracking studies. The last

section provides an overview of research on Spanish and Portuguese that has used eyetracking.

4. Spanish and Portuguese eyetracking studies

Eyetracking studies involving Spanish and Portuguese have grown in recent years. Due to space limitations, we will focus on studies examining L1 and L2 processing during comprehension in adults. In particular, we will summarize studies concerning lexical, morphological, and syntactic processing.

4.1 Lexical processing

Altarriba et al. (1996) investigated Spanish-English balanced bilinguals' processing of Spanish and English words in sentences with high and low constraint contexts. They found an interaction between word frequency and constraint type when the words appeared in Spanish but not in English. Also, the first fixation durations were longer for high-frequency Spanish words in the high-constraint sentences than in the low-constraint sentences, which the authors argued was due to the conceptual restrictions produced by the sentence context being met, whereas the lexical restrictions were not. More recently, Canseco-González, Brehm, Brick, Brown-Schmidt, Fischer & Wagner (2010) used eyetracking and a visual world paradigm to examine lexical access in English-Spanish bilinguals. Participants read target and lexical competitors and chose objects on a computer screen based on aural instructions, and the data revealed a within-language cohort effect in all bilingual groups, affected slightly by age of acquisition and a small between-language cohort effect in participants who had acquired the non-contextual language earlier in life. These results support non-selective models of bilingual word recognition, such as Dijkstra & Van Heuven's (2002) BIA+ model, and the authors noted that, unlike event-related potentials and cross-modal lexical priming, eyetracking "provides us with an on-line measure of lexical activation in each of a bilingual speaker's languages without the necessity of explicitly referring to the 'irrelevant' (or non-contextual) language" (p.673).

As for Portuguese, Ogusuko, Lukasova & Coutinho de Macedo (2008) explored whether beginning learners of Portuguese were sensitive to L2 word frequency and length. Participants read isolated words in L2 Portuguese, which varied in frequency, regularity, and length, and the results showed different fixation patterns from adult native readers. The authors proposed the need for new styles of teaching adults how to read.

4.2 Morphological processing

Eyetracking has also been used to investigate the processing of morphological information in the nominal and verbal domain. Keating (2009) investigated readers' sensitivity to noun-adjective gender violations in L1 and L2 Spanish based on the structural distance of the adjective to the noun being modified. He found that Spanish native speakers were sensitive to gender agreement violations with and without distance, that advanced learners of Spanish were only sensitive without distance (i.e. adjectives located within the DP), and that beginning and intermediate learners were not sensitive regardless of distance. By using eyetracking, Keating was able to analyze regression information to nouns and conclude that native-like knowledge of grammatical gender is acquirable by adult learners of L2, but that native-like processing of all types of gender agreement violations in the L2 may not be achievable.

With regard to verbal morphology, Ellis & Sagarra (2010) asked low proficiency English-Spanish adult learners to read sentences in Spanish (Spanish and English control groups read sentences in their L1) containing adverb-verb and verb-adverb congruencies/incongruencies and answer a comprehension question after each sentence. The findings suggested that native speakers of a morphologically rich language (Spanish monolinguals) rely more on morphological than lexical cues to resolve grammatical conflicts, and that, contrariwise, native speakers of a morphologically impoverished language (English monolinguals and late English-Spanish learners) behave the opposite way. Using similar stimuli with English-Spanish learners with and without L2 immersion experience, LaBrozzi (2009) reported that learners without immersion used lexical cues to resolve a tense conflict more than those with immersion, and concluded that an immersion experience helps classroom learners acquire native-like processing patterns. Furthermore, he found that study abroad learners with higher working memory capacity were better able to focus on morphological cues. In order to determine whether the learners' bias towards lexical cues is a general characteristic of the early stages of L2 learning or whether it is due to L1 transfer, Sagarra, Ellis & Gauthier (2011) asked English-Spanish and Romanian-Spanish late learners and three control groups (English, Romanian and Spanish monolinguals) to read similar sentences to those employed in Ellis & Sagarra (2010) in L2 Spanish (or their L2 for the controls) and choose one of four pictures after each sentence (two competing for meaning and two for form). The results revealed that (1) beginning learners relied so heavily on adverbs that they were insensitive to adverb-verb tense incongruencies unless they had high working memory capacity, (2) intermediate learners were sensitive to tense incongruencies but still relied more on adverbs independently of whether their L1 had impoverished (English) or rich (Romanian) morphology, and (3) advanced learners were sensitive to tense incongruencies, but those with L1 English relied more on adverbs whereas those with L1 Romanian

relied more on verbs. These findings inform linguistic and cognitive models of SLA and suggest that learners start with the least effortful interpretation and later on recur to L1 transfer. Seibert Hanson & Sagarra (2011) obtained similar eyetracking data with SVO and OVS sentences in L2 Spanish (flexible word order) by L1 Romanian (flexible word order) and L1 English (fixed word order).

4.3 Syntactic processing

Carreiras & Clifton (1999) used eyetracking to study relative clause attachment preferences. The findings replicated their previous self-paced reading studies except for an overall N2 disambiguation advantage in English, which was shown to be significant in eyetracking but null in self-paced reading. The authors concluded that, "the real effect can be captured when a sensitive enough measure is used" (p.830). Using the same stimuli from Carreiras & Clifton (1999), Dussias & Sagarra (2007) examined L2 influences on L1 sentence parsing. Spanish monolinguals and proficient Spanish-English bilinguals with limited and with extensive L2 immersion experience read sentences with temporarily ambiguous relative clauses. The results revealed that Spanish monolinguals and Spanish-English bilinguals with limited L2 immersion attached the relative clause to the first noun (high attachment), and that Spanish-English bilinguals with extensive L2 immersion attached it to the second noun (low attachment). The authors concluded that there is permeability of the L1 system, and that eyetracking as a method allowed them to gather evidence to support the Linguistic Tuning hypothesis (Mitchell & Cuetos 1991 and Cuetos, Mitchell & Corley 1996). More recently, Betancort, Carreiras & Sturt (2009) have used eyetracking to investigate animacy effects on subject and object relative clauses in Spanish. The findings showed that Spanish readers follow a subject relative preference, but that this preference is modulated by animacy.

Eyetracking has also been used to investigate code-switching. Dussias (2003) found that participants took longer to read code switches with *haber* + ENGLISH PARTICIPLE than those that occurred at the phrasal boundary, and that *estar* + ENGLISH PARTICIPLE code switches did not produce longer reading times. In a more recent code-switching eyetracking study using visual world paradigm, Valdés Kroff, Guzzardo, Dussias, Gerfen & Gullifer (2008) asked Spanish-English bilinguals to see pairs of objects presented in English-only, Spanish-only, and code-switching blocks with English words spoken with a Spanish article that matched or not the gender of the Spanish translation. The results showed differential processing of masculine and feminine articles in the code-switching block and the authors concluded that L2 speakers perform differently when processing mixed language than when processing in unilingual mode. As with the rest of the studies discussed in this section, the unique characteristics of eyetracking allowed for the discovery of important findings that have made a major contribution to linguistic theories.

5. Conclusion

We have examined the role of eyetracking in linguistics. To that end, we have discussed the benefits of this technique for linguistic research, we have provided technical information on eyetracking measures and eyetracker systems, and we have summarized some of the eyetracking studies on Spanish and Portuguese that use this methodology to address questions related to lexical, morphological and syntactic processing. Eyetracking has been shown to be superior to other online techniques and we hope that linguists can use this paper as a guide for interpreting eyetracking articles and for launching their own eyetracking studies.

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