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Event-related brain potentials reveal age-related changes in parafoveal-foveal integration during sentence processing☆

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ABSTRACT

Normative aging is associated with deficits in visual acuity and cognitive control that impact the allocation of visual attention, but little is known about how those changes affect information extraction and integration during visual language comprehension in older adulthood. In the current study, we used a visual hemi-field flanker RSVP paradigm with event-related brain potentials to study how older readers process fine-grained aspects of semantic expectancy in parafoveal and foveal vision. Stimuli consisted of high constraint sentences with expected, unexpected but plausible, or anomalous parafoveal target words, as well as low constraint sentences with neutral but expected target words. Older adults showed graded parafoveal N400 effects that were strikingly similar to younger readers, indicating intact parafoveal semantic processing. However, whereas young adults were able to use this parafoveal pre-processing to facilitate subsequent foveal viewing, resulting in a reduced foveal N400 effect, older adults were not able to. Instead, older adults re-processed the semantics of words in foveal vision, resulting in a *larger* foveal N400 effect relative to the young. Collectively, our findings suggest that although parafoveal semantic processing per se is preserved in aging, there exists an age-related deficit in the ability to rapidly integrate parafoveal and foveal visual semantic representations.

1. Introduction

Although skilled readers may have the subjective experience that they can clearly perceive words across a large portion of the visual field in a single fixation (e.g., a line or even an entire page of text), in reality, readers are unable to fully process information outside of foveal vision. Acuity drops off rapidly in the parafoveal region, corresponding to approximately 2–5° on either side of the vertical meridian, and further so in peripheral vision. The *perceptual span*, which is the region in which useful visual features can be processed in a given fixation in reading, is asymmetric—skewing in the direction of reading. In English, it ranges from about 3–4 character spaces to the left of a fixation to upwards of 15 characters to the right of fixation (see Rayner, 2009 for a review). Current questions in reading research concern delineating the nature and quality of information that can be extracted from parafoveal vision and understanding how that information is used in the course of subsequent reading (e.g., Schotter et al., 2012 for a review).

One factor that may importantly affect parafoveal processing during reading is aging. Age-related changes in sensory and cognitive systems have a substantial impact on multiple aspects of language comprehension (see Shafto and Tyler, 2014; Stine-Morrow and Payne, 2016; Wlotko et al., 2012). These changes are likely to influence older adults' allocation of visual attention during reading and their ability to process information in the parafovea. However, few studies have examined age-related changes in parafoveal processing or the ability to use parafoveal preview information during reading. In the current study, we examined age-related changes in neural indices of parafoveal processing during reading by measuring event-related brain potentials (ERPs) in a modified flanker-RSVP paradigm that affords the simultaneous investigation of neural indices of parafoveal and foveal processing in real time during reading. Specifically, we examined how normative aging impacts (1) the processing of words in parafoveal vision that vary in semantic expectancy and congruity with respect to their preceding context, and (2) how parafoveal semantic processing influences subsequent foveal viewing (i.e., parafoveal-to-foveal integration).

2. Parafoveal vision and reading

Eye-movement research forms the primary evidence base for the current understanding of parafoveal processing during reading and has

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provided valuable insight into how information across foveal and parafoveal vision is processed and integrated during reading (Clifton et al., 2016; Rayner et al., 2009; Schotter et al., 2012). A number of clever eye-tracking paradigms have been developed to study the dynamics of the perceptual span and parafoveal processing in natural reading (see Schotter et al., 2012, for a review). For example, in the gaze-contingent boundary change paradigm (McConkie and Rayner, 1975), an invisible boundary is placed between the fixated word (*n*) and the word to the right of fixation ($n + 1$). When the eyes cross the invisible boundary, a change in the display is triggered, which is used to manipulate the availability of useful parafoveal information. On selected trials, $n + 1$ is initially replaced by a masking stimulus (e.g., a different word or a string of characters or X's) and, as the reader saccades from *n* to $n + 1$, the mask is replaced with the target word. Thus, the logic of this paradigm is that by comparing fixation durations and eye-movements on word $n+1$ between conditions where different information was presented parafoveally, one can infer what kind of information was extracted from parafoveal vision. Indeed, this paradigm has revealed a characteristic *parafoveal preview benefit*: When a reader receives a valid preview of word $n + 1$, fixation durations on that word are 30–50 ms shorter relative to trials in which word *n* was initially replaced with an invalid mask, suggesting that some level of preprocessing of $n + 1$ occurred when the eyes were fixating word *n* and that features of parafoveal and foveal words are rapidly integrated across successive saccades (Hyönä et al., 2004; Schotter et al., 2012), though at least a portion of this reflects a preview *cost* due to processing the invalid parafoveal masking stimulus (e.g., Kliegl et al., 2013).

Research using the boundary change paradigm while manipulating linguistic features of the parafoveal mask (orthographic, phonological, semantic) has largely formed the basis of our knowledge of the kind of information that can be extracted from parafoveal vision and integrated with subsequent foveal processing. This work has converged on the finding that readers can extract and integrate parafoveal orthographic information as well as abstract phonological codes (see Vasilev and Angele, 2017 for a recent meta-analysis). However, early on, semantic information was thought to not be extracted from parafoveal vision. For example, a number of studies found no evidence for lexical priming from the parafoveal word (Rayner et al., 1986; Dimigen et al., 2012). Moreover, there was a lack of evidence for lexical or morphological parafoveal preview benefits in reading (Bertram and Hyönä, 2007; Inhoff and Rayner, 1986; Altarriba et al., 2001; Rayner et al., 1986; Rayner et al., 2014).

More recent work, however, has found evidence for the extraction of semantic features from parafoveal vision. For example, morphologically rich languages such as Mandarin (Yan et al., 2009) and German (Hohenstein et al., 2010) have provided evidence for semantic parafoveal preview. In English as well, a growing literature suggests that attention can be allocated to semantic processing in parafoveal vision. For example, semantic parafoveal effects are obtained when previews are available for short periods of time (Hohenstein et al., 2010), when parafoveal previews are synonyms (Schotter, 2013), or when previews are embedded within highly constraining sentence contexts (Schotter et al., 2015; Barber et al., 2010; Barber et al., 2013; Veldre and Andrews, 2015), with congruency-based parafoveal preview benefits observed in eye-movement behavior and electrophysiology (discussed in more detail below). Nevertheless, there is still ongoing debate regarding the nature and scope of semantic extraction from parafoveal vision (Rayner et al., 2014; Clifton et al., 2016; Dimigen et al., 2012; Johnson and Dunne, 2012; Snell et al., 2017).

3. Aging, parafoveal processing, and "risky" reading

Normative aging is associated with widespread changes in central and peripheral visual acuity (e.g., contrast sensitivity, retinal illumination, visual processing speed, and useful field of view), as well as an increased risk for the development of visual pathology (e.g., macular degeneration, glaucoma, and cataracts; Owsley, 2011 for a review), all of which can lead to difficulties with reading fluency and comprehension with advancing age (e.g., Sass et al., 2006; Legge et al., 1992; Payne and Stine-Morrow, 2016). At the same time, normative age-related neuroanatomical and functional changes, particularly in frontal and pre-frontal cortex, result in a range of declines in cognitive functioning, particularly for tasks that place strong demands on attention, executive control, and working memory (e.g., Fabiani, 2012; Grady, 2008; Fjell and Walhovd, 2010).

One way that normative age-related changes in sensory and cognitive function may affect visual language comprehension is by influencing how attention is allocated to foveal and parafoveal information (Rayner et al., 2006; Payne and Stine-Morrow, 2012). Older adults not only read more slowly (Payne and Stine-Morrow, 2012; Rayner et al., 2006), but also more variably (Payne and Stine-Morrow, 2014), and sometimes show greater rates of regressive eye-movements (Rayner et al., 2006, 2009, 2013). In non-reading domains, aging is associated with less efficient uptake of extra-foveal information (Ball et al., 1988; Sekuler et al., 2000). At the same time, only a small number of studies have examined the effects of aging on parafoveal processing in reading. These studies have revealed that older adults have a reduced and less asymmetric perceptual span (Rayner et al., 2009), extract less information from the word immediately to the right of fixation in parafoveal vision (Rayner et al., 2010; Payne and Stine-Morrow, 2012), and are less capable of using parafoveal vision to guide reading when foveal processing is impaired (via an artificial foveal scotoma; Rayner et al., 2014). At the same time, other research has found evidence for preserved parafoveal processing or even differential sensitivity to extrafoveal information in reading. For example, Risse and Kliegl (2014) found that older adults were sensitive to lexical status two words to the right of fixation ($n + 2$), and Paterson et al. (2013) found that older adults showed sensitivity to manipulations of spatial frequency in reading that were more diffuse across the visual field than younger adults. Importantly, the amount of information derived from parafoveal vision in aging may be largely dependent upon the concurrent cognitive workload of foveal processing. For example, Payne and Stine-Morrow (2012) found that older adults showed comparable parafoveal preview benefits to young adults when the difficulty of foveal processing was low. However, when a substantial foveal *load* (i.e, Henderson and Ferreira, 1990; Payne et al., 2016) was induced, older adults' parafoveal preview benefits were differentially reduced relative to the young (Payne and Stine-Morrow, 2012), suggesting that either the extraction or integration of parafoveal information was disrupted in aging.

Rayner et al. (2006, 2009, 2013) have argued that older adults adopt a series of strategies to compensate for age-related slowing of lexical processing, resulting in what has been termed *risky reading*. According to the risky reader theory, to maintain a fluent reading rate older adults rely differentially on noisy and incomplete parafoveal visual information to "guess" the identity of upcoming words, leading to increased word skipping rates. However, because of age-related declines in parafoveal visual acuity, parafoveal words are often incorrectly identified, resulting in a greater rate of disruption (e.g., regressions) to normal reading (though see Choi et al., 2017). In particular, Rayner et al. (2006) have argued that older readers will differentially rely on prior contextual constraints to make inferences about lexical items in parafoveal vision, despite reductions in parafoveal perception. However, a substantial electrophysiological literature has amassed indicating that older adults do not use context as effectively as do young adults, and, in particular, are less likely to use contextual constraints to engage in anticipatory or predictive processing (Federmeier et al., 2002, 2010; Payne and Federmeier, 2017; Wlotko et al., 2012; see Wlotko et al., 2010 for a review). One limitation in comparing these bodies of work is that nearly all electrophysiological and neuroimaging research on age differences in visual language processing has used single word presentation, which precludes the utilization of parafoveal information during reading. At the