EFFECTS OF EFFICIENT FRONTO-TEMPORAL CIRCUITRY ON LEXICAL AMBIGUITY RESOLUTION: CONVERGING EVIDENCE FROM CROSS-AGE COMPARISONS IN EYE-TRACKING AND ERP DATA

BY

MALLORY STITES

THESIS

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Adviser:

Associate Professor Kara D. Federmeier
Abstract

Eye-tracking was used to examine how younger and older adults use syntactic and semantic information to disambiguate noun/verb (NV) homographs (e.g., park). We find that young adults exhibit inflated first fixations to NV-homographs when only syntactic cues are available for disambiguation (i.e., in syntactic prose). This effect is eliminated with the addition of disambiguating semantic information. Older adults (60+) as a group fail to show the first fixation effect in syntactic prose; they instead reread NV homographs longer. This pattern mirrors that in prior event-related potential work (Lee & Federmeier, 2009, 2011), which reported a sustained frontal negativity to NV-homographs in syntactic prose for young adults, which was eliminated by semantic constraints. The frontal negativity was not observed in older adults as a group, although older adults with high verbal fluency showed the young-like pattern. Analyses of individual differences in eye-tracking patterns revealed a similar effect of verbal fluency in both young and older adults: high verbal fluency groups of both ages show larger first fixation effects, while low verbal fluency groups show larger downstream costs (rereading and/or refixating NV homographs). Jointly, the eye-tracking and ERP data suggest that effortful meaning selection recruits frontal brain areas important for suppressing contextually inappropriate meanings, which also slows eye movements. Efficacy of fronto-temporal circuitry, as captured by verbal fluency, predicts the success of engaging these mechanisms in both young and older adults. Failure to recruit these processes requires compensatory rereading or leads to comprehension failures (Lee & Federmeier, in press).
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Introduction

The English language is full of one-to-many mappings, in which an identical written wordform can represent a number of distinct meanings. However, readers have the ability to move easily from written form to meaning, without a noticeable delay between apprehension and comprehension. It remains one of the main goals of psycholinguistic research, then, to understand the processes underlying lexical ambiguity resolution, and furthermore, how these processes change with advancing age. Unfortunately, there has been little agreement across methods as to the nature of certain online ambiguity resolution processes, which is a necessary first step to understanding age-related effects. The current study will seek to reconcile discrepancies found across two methodologies widely used to study online language comprehension, event-related potentials (ERPs) and eye-tracking, and to understand how ambiguity effects play out in both young and older adults.

Within-Class Ambiguity Resolution

There are two main types of lexical ambiguity, those of words whose meanings fall within a single syntactic class (e.g., calf), henceforth noun/noun (NN) homographs, and those with meanings that fall into different syntactic classes (e.g., park), noun/verb (NV) homographs. Work across various methodologies has found that two key pieces of information best determine the processing costs associated with NN homographs: the preceding context and meaning frequency. For words with two equally-likely meanings (i.e. balanced homographs), eye-tracking results have consistently found increased reading times compared to unambiguous words when the preceding context is semantically neutral, an effect thought to reflect competition for selection between the two equally-activated meanings (Rayner & Frazier, 1989). In contrast,
when the context biases interpretation towards one meaning, reading times are indistinguishable from unambiguous words. A second well-characterized eye-tracking result is the subordinate bias effect (Rayner, Pacht & Duffy, 1994). In this phenomenon, reading times on biased NN homographs (whose meanings are of unequal frequencies) are longer relative to unambiguous words, but only when the preceding context instantiates the subordinate, or less frequent, meaning. This effect has been explained by the reordered access model as reflecting competition between the two meanings, because the dominant sense is impossible to completely suppress despite the subordinate-biased context (Duffy, Morris, Rayner, 1988).

Like the eye-movement literature, ERP studies have also shown that the interactions between lexical and contextual factors play a key role in determining ambiguity effects for NN homographs. Swaab, Brown and Hagoort (2003) demonstrated that in spoken language comprehension, both meanings of ambiguous words are partly activated initially, regardless of context. However, the dominant meaning is harder to suppress and active longer in an inappropriate context than the subordinate meaning. Gunter, Wagner and Friederici (2003) further showed that a reader’s working memory span significantly affects his or her ability to suppress an ambiguous word’s dominant meaning in an inappropriate context. Additionally, Meyer and Federmeier (2007) found that the two cerebral hemispheres utilize context information differently in the meaning selection of ambiguous words, suggesting that there may be multiple mechanisms at work in lexical ambiguity resolution. At the highest level, the ERP work reinforces the idea put forth by previous work that the interplay between context and meaning dominance is quite complex. Understanding how each contributes is critical to reaching a fuller understanding how readers process ambiguous words.
Across methods, the literature involving NN homographs has converged to show that the dominant meaning of a biased ambiguous word is easier to activate and harder to suppress than its subordinate meaning. Importantly, the preceding context exerts a large influence over how much activation each meaning receives, thus determining whether there will be competition between the two meanings and the associated processing costs. Given the importance of context in meaning resolution, a critical question is, which aspects of context are most important? Biasing sentential contexts typically provide both semantic and syntactic cues as to the identity of the upcoming word. In the case of NN homographs, whose meanings fall into the same syntactic category, it is difficult to distinguish the separate contributions of semantics and syntax. However, in the case of NV homographs, which are both semantically and syntactically ambiguous, it becomes possible to examine the contributions of each type of context separately. Here, findings across methods have been much less consistent, and it is this question that the current study aims to address.

Across-Class Ambiguity Resolution

Behavioral and ERP Evidence

Past behavioral studies of NV homograph processing using cross-modal priming originally found that both meanings of NV homographs are active despite disambiguating syntax. Tanenhaus, Leiman and Seidenberg (1979) found that both meanings of a NV homograph are initially activated, as evidenced by facilitated naming times for targets related to either sense of the word when presented immediately following it in a semantically neutral, but syntactically constraining sentence (i.e. I bought the watch / I will watch), but not when presented at a 200 ms delay. Other similar studies replicated this basic finding (Seidenberg,
Tanenhaus, Leiman & Bienkowski, 1982; Tyler & Marslen-Wilson, 1977). Together, these results were taken as evidence for a multiple-access account of lexical ambiguity resolution, in which both meanings of NV homographs are initially activated regardless of syntactic cues, before suppression of the contextually inappropriate meaning.

Recent ERP work by Lee and Federmeier (2009) has found evidence that qualitatively different processing takes place for NV homographs and unambiguous words depending on the type of preceding context readers receive. Their study will be discussed in some detail, as the current experiment makes use of exactly the same design. Lee and Federmeier (2009) created two types of sentences to test for the independent contributions of syntax and semantics. First, congruent sentences were created that were both semantically and syntactically coherent with only one interpretation (noun or verb sense) of the homograph (e.g. *A key strategy to winning in a poker game is to bluff*). The second sentence type, syntactic prose sentences, maintained the same syntactic structure but lacked coherent semantics (e.g., *A surprised shirt to winning in a time girl is to bluff*). These sentences were created by exchanging the content words (nouns, verbs, adjectives, etc.) of a given coherent sentence with randomly selected content words from other coherent sentences, while leaving intact all of the function words as well as the sentence-final NV homograph. This ensured that the sentences maintained the same predictive syntactic structure while lacking a coherent meaning, allowing the effects of syntax alone to be compared with the combined effects of syntactic and semantic constraints.

When ERPs were examined time-locked to the onset of the ambiguous words, the NV homographs elicited responses that were more negative, compared to controls, over the frontal channels between approximately 200 and 700 milliseconds post-stimulus onset, but only in the syntactic prose sentences. In the congruent context, the waveforms elicited by the two word
types were indistinguishable over the frontal channels, suggesting that the addition of rich semantics to the well-defined syntax eliminated the processing costs for the class-ambiguous words. This finding replicated those from several previous studies, which also found frontal negativity to NV homographs in the presence of syntactic, but not semantic, constraints (Federmeier, Segal, Lombrozo and Kutas, 2000; Lee & Federmeier, 2006).

Additionally, Lee and Federmeier (2009) found a reduction of N400 amplitude for both ambiguous and unambiguous words in the congruent compared to syntactic prose sentences. The N400, a negative-going waveform that peaks around 400 milliseconds post-stimulus onset and is largest over central-parietal electrode sites, is part of the normal brain response to words and other meaningful stimuli (see Kutas & Federmeier, 2011, for a review). The amplitude of the N400 elicited by open-class words is typically reduced as a function of their serial sentence position, representing the build-up of semantic information throughout the sentence that eases processing on those words (Van Petten & Kutas, 1990). Since the syntactic prose condition offered no message-level semantics, this accumulative effect of context information would not be expected to occur. However, while N400 reductions were seen for both types of words in the congruent context, the amount of reduction was greater for unambiguous than ambiguous words, even though their expectancy was matched. In a second experiment, Lee and Federmeier (2009) found that the larger N400 amplitudes for ambiguous words were driven by cases in which the context instantiated the subordinate sense of the word, suggesting residual activation of the dominant meaning. In contrast, when the context picked out the dominant meaning, the waveforms elicited by ambiguous and unambiguous words were indistinguishable. This effect could be thought of as an analogue to the subordinate bias effect from the eye-tracking literature, in which there is increased processing when context picks out the subordinate sense of
ambiguous words, likely due to readers’ inability to fully suppress the word’s dominant meaning. In spite of these ambiguity effects on the N400, there was no frontal negativity effect, showing that the presence of semantically constraining information eliminates some of the processing costs associated with NV homographs.

Findings from recent ERP studies consistently show that the processing of NV homographs is multi-faceted, and dependent upon the available cues provided by the preceding context. The ERP findings converge with the behavioral results to suggest that in syntactically well-defined but semantically neutral or impoverished contexts, NV homographs are processed qualitatively differently from unambiguous words, reflected by the frontal negativity effect. This effect has been posited to reflect the recruitment of frontally-mediated selection mechanisms to aid in difficult meaning selection when semantic constraints are unavailable. These processes must be recruited to help suppress the context-inappropriate meaning of the target word when readers have only syntactic cues.

To investigate the locus the frontal negativity effects, Lee and Federmeier (2011) tested a set of older adult participants using the same materials. Previous findings have shown that older adults experience both biological and cognitive declines, in the form of deterioration of the frontal lobe (Raz et al., 2005), as well in their reduced abilities to engage controlled, top-down processes (DiGirolamo et al., 2001). However, they appear to have largely intact language processing abilities, especially for automatic processes like semantic associations (Burke & Peters, 1986) and automatic aspects of semantic priming (Burke & Harrold, 1993). This leaves the open question of what type ambiguity resolution processes older adults might engage in, especially for NV homographs in semantically impoverished contexts. Previous studies exploring ambiguity resolution processes of older adults have found mixed results, but the
overarching effects seem to suggest that they are just as good as younger adults at using semantic information to resolve ambiguities online (Balota & Duchek, 1991; Hopkins, Kellas, & Paul, 1995; Meyer & Federmeier, 2010; Swaab, Brown and Hagoort, 1998), but that they fail to use syntactic cues online when the context is semantically neutral (Dagerman, MacDonald, & Harm, 2006). This inability to use syntactic cues in online ambiguity resolution, partnered with their frontal lobe deterioration, it is perhaps unsurprising that Lee and Federmeier (2011) found that older adults as a group did not exhibit the frontal negativity effect exhibited by the young adults in Lee and Federmeier (2009). This suggests that older adults were unable to recruit these frontally-mediated selection mechanisms, and thus likely did not perform meaning selection online. Interestingly, though, older adults with high verbal fluency showed the young-like effect. This was not the first time that higher verbal fluency has been found to predict young-like language processing abilities in older adults (Federmeier et al., 2002; Federmeier, Kutas, & Schul, 2010) and suggests that verbal fluency reflects the efficacy of an individuals’ ability to quickly engage their frontal circuitry underlying the selection mechanisms. Thus, the ERP results tell quite a clear story: processing of NV homographs differs from that of unambiguous words in the face of only syntactic constraints. Readers need to recruit additional processing mechanisms to aid in difficult meaning selection. Young adults seem able to do so online, whereas older adults as a group do not. However, those with high verbal fluency exhibit young-like, although slightly weaker, effects.

Eye-Tracking Evidence

While the results from ERPs are quite consistent, eye-tracking results not only conflict with those from ERPs, but are also inconsistent within the field itself. Fraizer and Rayner (1987)
originally proposed that readers delay selecting a meaning of NV homographs until enough information becomes available to do so. This theory was supported by their results showing longer gaze durations on class-ambiguous phrases (e.g., *desert trains*, which could be interpreted as either noun-verb or adjective-noun) following disambiguating modifiers (e.g., *this* or *these*) than following the ambiguous modifier *the*. Conversely, reading times on semantically disambiguating regions following the phrases were longer after the ambiguous modifier. Together, these findings were interpreted as showing that when readers did not have enough information to resolve the phrase’s ambiguity initially, they delayed assigning syntactic class (and thus the associated reading time cost) until more information became available later in the sentence. However, MacDonald (1993) also found increased gaze durations on inherently unambiguous phrases (e.g. *desert trained* or *deserted trains*) following the so-called disambiguating modifiers (*this*/*these*). These subsequent effects were attributed to the confusing use of the deictic modifiers *this* and *these* in contexts that lacked specific referents, rather than reflecting syntactic class assignment of the phrase. Thus, MacDonald (1993) called into question the validity of Frazier and Rayner’s (1987) findings, and by extension, the delay strategy they proposed.

Another more recent eye-tracking study by Folk and Morris (2003) addressed the question of how readers resolve NV homographs. Biased NN and NV homographs were embedded in sentences that instantiated the word’s meaning through both semantic and syntactic context (e.g. *Biking through Utah, the cyclist lost a spoke in the mountains*). While the typical subordinate bias effect was observed for the NN homographs, this effect was absent on the NV homographs. That is, gaze durations were not inflated on these words when the subordinate meaning of the NV homograph was intended, suggesting that the context provided enough
information to selectively activate only the subordinate meaning of the word. In Experiment 2 of this study, balanced NN and NV homographs were embedded in sentences that were semantically neutral, but syntactically instantiated the word’s noun sense (e.g. *Laurie took the prune out of the fruit bowl and ate it*). Results showed longer gaze durations on the balanced NN homographs compared to unambiguous controls, which is in line with previous findings (Rayner & Frazier, 1989). However, neither reading times on the NV homographs themselves nor for the remainder of the sentence were longer compared to unambiguous controls. Taken together with the lack of a subordinate bias effect on their biased homographs, the authors concluded that syntax alone provided enough information to allow readers to preselect the correct meaning of the NV homograph, eliminating typical ambiguity costs.

Since the eye-tracking effects seen in response to the processing of noun/verb homographs are not well defined, it is even less clear what kinds of age-related differences we might find. There are some generally accepted age-related differences in eye movement patterns, though. For example, older adults have longer overall reading times (Stine-Morrow, Soederberg Miller, & Hertzog, 2006), and make longer fixations on individual words (Kliegl, Grabner, Rolfs, & Engbert, 2004). They have also been shown to have smaller perceptual spans than young adult readers (Rayner, Castelhano, & Yang, 2009), although they have a higher rate of word skipping (Rayner et al 2006) and also make more regressions back in text (Kemper, Crow, & Kemtes, 04). Because of these characteristics, older adults have sometimes been characterized as ‘risky’ readers (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006), in that they rely on partial parafoveal information to predict (and skip) upcoming words more often than younger readers. However, while word skipping is typically thought to indicate that the skipped word was processed on the reader’s previous fixation (Rayner, 1998), the fact that older adults also return
more often to skipped words than younger adults suggests that their prediction is not always successful. This theory is bolstered by evidence from the ERP literature that older adults are less able to use contextual information to preactivate upcoming words (Federmeier & Kutas, 2005) and thus may have reduced prediction capabilities in natural reading as well.

Despite different overall reading patterns, older adults show slightly larger frequency effects than young adults (i.e., increased reading times on infrequent compared to frequent words), while effects of predictability are of at least equal magnitude for both age groups (Rayner et al., 2006). However, no known studies have investigated how older adults resolve the ambiguity associated with NV homographs in natural reading. While frequency effects are present in both older adults, they are a consequence of stimulus-driven factors, which have been shown to be largely maintained in older adults (DiGirolamo et al., 2001). To the extent that NV homograph resolution is a more controlled process, as suggested by the ERP findings, then we might expect differences in possible eye-tracking effects based on older adults’ reduced ability to engage top-down mechanisms. Furthermore, previous studies of older adults’ NV homograph resolution strategies presented materials at a predetermined rate. As Stine-Morrow and colleagues have found that older adults strategically allocate their processing resources over text differently than young adults do, (Stine-Morrow et al., 2006), age-related effects may be present in eye-tracking, in which older adults have more strategic control over the timing and order that they take in information.

The Current Study

Thus, whereas behavioral and ERP measures have consistently suggested that syntactic cues alone are insufficient to resolve the semantic ambiguity associated with NV-homographs
without entailing the recruitment of additional processes, some eye-tracking findings have pointed to the possibility that syntactic cues may be effective for resolving this ambiguity in ways that semantic cues are not (for example, allowing the selection of even subordinate meanings). However, the inconsistencies across eye-tracking studies -- and across measures more generally -- points to the need for further research.

Past eye-tracking and ERP studies have found disparate results, but the experimental conditions employed have been quite different as well. For instance, Folk and Morris (2003) used only the noun interpretation of the NV homographs in their semantically neutral contexts. If subjects implicitly learned this pattern, it may have changed their reading strategies on these words, possibly reducing ambiguity effects that may have manifested otherwise. Perhaps, then, if the stimuli included both the noun and verb meanings, reading times would reflect the processing differences seen in the ERP experiments. On the other hand, it is also possible that the effects seen in the ERPs index increased brain activity that has no behavioral consequences. If subjects were free to read the stimuli from the ERP experiments naturally, there may not be observable behavioral correlates of the frontal negativity seen to the ambiguous words.

The current study aims to address three questions. The first question asks why the ERP and eye-tracking literature have found such different ambiguity effects associated with NV homographs. To address this discrepancy, we will collect eye-tracking measures during natural reading using the stimuli employed in Lee and Federmeier’s (2009, 2011) ERP studies, which have been shown to produce robust ERP ambiguity effects. We aim to discover whether there are behavioral consequences associated with the previously observed ERP ambiguity effects when readers are free to control their own eye movements. This design will allow for the first
direct comparison of ERP and eye-tracking indices in the domain of ambiguity resolution, providing the unique opportunity for the two measures to inform interpretations one another.

Secondly, we want to determine whether there are age-related differences in the ambiguity effects seen in natural reading. Since the resolution of noun/verb homographs in the syntactic prose contexts is thought to require the recruitment of top-down meaning selection mechanisms, and being that we see these effects in the ERPs for young but not older adults, we predict that there may be qualitatively different effects for the two age groups. Finally, based on the modulation of age effects by verbal fluency in the ERP findings (Lee and Federmeier, 2011), we ask whether verbal fluency may also modulate possible age-related effects in natural reading as well. As such, we will collect measures of verbal fluency for these groups in order to test for the effect of verbal fluency in our results.
Experiment 1: Young Adults

Methods

Materials

The critical stimuli are the same as those used in Experiment 1 of Lee & Federmeier (2009). There were two categories of target words: NV homographs, whose meanings are both semantically and syntactically ambiguous (e.g. the park / to park), as well as semantically and syntactically unambiguous words (e.g. the logic / to choose). These words were used to end critical sentences that were of two distinct types. The first sentence type was congruent sentences, which had both coherent semantic and syntactic contexts (e.g. The children loved the swings and were excited when their mom took them to the park). The second type, syntactic prose, had clear syntactic context but lacked meaningful semantics (e.g. The horses broke the try-outs and were weighed when their woman loved them to the park). To create syntactic prose sentences, content words from the congruent sentences were randomly exchanged with those from other congruent sentences, while the function words and sentence-final target words remained intact. In this way, the syntactic prose sentences were syntactically correct and still clearly instantiated one meaning of the ambiguous words, but they lacked any clear message-level semantics. Word type and sentence type were fully crossed, creating four experimental conditions. A filler condition was also created in which the words from the syntactic prose sentences were scrambled, up to the target word. The scrambled sentences were included so that readers would not be able to predict whether syntactic or semantic information would be available from trial to trial.

Each critical sentence described above was presented on the screen along with a follow-up sentence. The follow-up sentences were intended to reduce wrap-up effects on the sentence-
final target words, while also allowing for regressive movements back to these words. Follow-up sentences for the congruent context were coherent continuations of the topic of the critical sentence, while the syntactic prose and random follow-up sentences were created in the same way as the syntactic prose sentences, as follow-up sentences for these two conditions were identical. Table 1 contains example critical and follow-up sentences for the congruent and syntactic prose contexts.

Subjects read 344 sentences, 172 each of critical and follow-up sentences. Six lists were generated so that target words could be rotated through all three sentence conditions in both their noun and verb sense. Each list was randomized once, and then presented to subjects in the same randomized order. Subjects saw only one of the lists, so that they saw every target word once, and saw at least 28 items in each of the six conditions. The noun-verb homographs were equally likely to appear as a noun or a verb, and were always placed in a sentential context that clearly supported one meaning. The unambiguous words always appeared in appropriate syntactic frames. There were equal numbers of appearances of ambiguous and unambiguous words within each sentential context. The number of nouns and verbs was also matched across the ambiguous and unambiguous word sets.

The target words were matched across conditions, both experiment-wide and within each list, for several important linguistic characteristics. Target words were matched on their log-frequency (Francis & Kucera, 1967), word length, and usage-specific concreteness (Lee & Federmeier, 2006). Also considered was the semantic distinctiveness of the homographs (i.e. the similarity of their noun and verb meanings), which was normed by Lee and Federmeier (2006), and controlled across context types.
The critical sentences were also matched on a range of features. Sentence length was equated across conditions, as was cloze probability and plausibility (Lee & Federmeier, 2009). To assess cloze probability, a different group of subjects was given the sentence frames up to (but excluding) the target word, and asked to complete the sentence. For the plausibility ratings, another group of subjects was given the sentences to read and asked to rate them on a scale of 1-7, where 1 represents “makes no sense at all” and 7 represents “makes perfect sense.” The sentences chosen for use in the current study had an average cloze probability rating of 50% and an average plausibility rating of 6.5 (For further details, refer to Lee & Federmeier, 2009).

Participants

Eighteen UIUC undergraduate and graduate students (9 males; mean age 20.4 years, range 18-26) participated in the eye-tracking portion of the study for cash or course credit. All were right-handed, as assessed by the Edinburgh inventory (Oldfield, 1971). Eleven participants reported having at least one left-handed family member. All were monolingual speakers of English, with no consistent exposure to another language before the age of five. Participants also had no history of neurological disease, psychiatric disorders or brain damage. Each was randomly assigned to a different experimental list.

Procedure

Subjects were run individually in a quiet room, where they were seated 97 cm away from a 19-inch ViewSonic P225f monitor (resolution of 1024 x 768), with a refresh rate of 120 Hz. Before the experiment began, the head-mounted SR research Eyelink II eye-tracker was fitted and calibrated for each subject. A chin rest was used to reduce head movements. Recordings
were monocular, taken from the eye determined by the Eyelink software to have the more accurate calibration and validation readings.

Subjects were presented with written instructions, after which they received nine practice trials before the experiment began to allow them to become acclimated to the trial sequence. Each trial began with the appearance of a drift check target, which appeared in the upper-left corner of the screen. Subjects controlled the start of each trial by fixating the drift-check target while simultaneously pressing the advance button with on the left side of the hand-held controller. The trial then appeared on the screen, which consisted of a critical sentence and a follow-up sentence, starting in the top left-hand corner of the screen. Sentences were presented in white, upper case letters on a black background in size 30 Courier New Font, of which three characters constituted 1 degree of visual angle. Subjects were instructed to read the sentences normally, and press the advance button on the controller when they were finished. The experimental sentences were followed by a probe word that was presented in the center of the screen; subjects judged whether the probe word was or was not in the previous trial by pressing designated “Yes” and “No” buttons on the controller, both of which were pressed with the right hand. Half of the probes were new and half were old. Of the old words, half were content words chosen randomly from the previous trial, and half were the sentence final target words. This task was included to insure that subjects were attending to the stimuli, especially in the syntactic prose and filler conditions. With the button press, the trial was completed, and the next trial began with the appearance of the drift-check in the upper-left corner of the screen. The experiment was divided into four blocks consisting of 42-44 trials, each of which took an average of 7-8 minutes to read.
After each block, subjects were given a sentence recognition task to complete on paper. In this task, they were presented with sentences, with equal numbers in each of the three context types, half of which were presented in the previous block and half of which were not. Of the new sentences, all were taken from other experimental lists, meaning that there would be lexical item overlap between the old and new sentences, ensuring that subjects had to attend to more than word-level information to answer correctly. Subjects were asked to place a check next to items that they believed were seen in the previous block. This task, like the probe word task, was intended as a check to ensure that subjects were attending to all sentences. The time spent completing this task also served as a break between blocks, as subjects were allowed to move their heads out of the chin rest, and the headset could also be removed, if desired. Each experimental session lasted approximately 80 minutes, including set-up and practice trials.

Following the eye-tracking portion of the experiment, neuropsychological tests were administered after a short break. These tests included an assessment of working memory (reading span test; Daneman & Carpenter, 1980), response suppression/inhibiton (Hayling test; Burgess & Shallice, 1996), and executive function (verbal fluency tests, including letter fluency [FAS] and category fluency [animals, fruits and vegetables and first names]; Benton & Hamsher, 1978). For the reading span test, participants read aloud sentences in groups progressing from two up to six sentences (with five sets within each span size), and at the end of each group were asked to recall the last word in each sentence. Performance was measured by assessing each participant’s set size (the highest set size for which the participant recalled all items in at least three of the five groups), and the total number of items recalled. The average set size was 2.6 ($SD = 0.44$; range 2-3.5), and the average total number of words recalled was 54.8 ($SD = 10.72$; range 30-69). For the Hayling test, participants were given sentences frames missing the last word, and had to
provide a congruent ending (for phase I of the test), or an anomalous ending (for phase II).

Performance was measured by how many total trials participants provided the correct response required by the task. The average number of congruent endings (out of 24 trials) was 23.5 (SD = 0.62; range 22-24), and the average number of correct anomalous endings was 22.1 (SD = 1.50; range 18-24). For the fluency tests, participants were instructed to orally generate words that began with the letters F, A, and S in three separate 1-minute periods (for the letter fluency test), and to orally generate words that fall into the categories of animals, fruits and vegetables, and first names (for the category fluency test), again in three separate 1-minute periods. Participants generated, on average, 45.2 words in the letter fluency test (SD = 10.42; range 32-67), and 70.2 words in the category fluency test (SD = 14.52; range 52-114), creating an average combined score of 115.4 (SD = 22.80; range 84-177).

Data Analysis

Within the Eyelink II data analysis package, single fixations that were shorter than 80 milliseconds (ms) or longer than 800 ms were automatically excluded. Fixations shorter than 80 ms are unlikely to represent meaningful cognitive processing (Rayner, 1998), while fixations longer than 800 ms are likely the result of cases in which the tracker temporarily lost the eye, causing inaccurately inflated reading times. Some trials were also discarded due to track loss of the entire trial or program error. After all excluded fixations are taken into account, the minimum number of fixations per subject in each condition of interest was three, and the maximum was twenty-three. Overall, comparable numbers of fixations were included in each condition; Table 2 lists a summary of these counts.
Results

Behavioral Results

Word recognition task.

Overall accuracy for the word recognition task for young adults was 94%, showing that participants were attending to the sentences closely enough to remember individual words. Memory performance was assessed using the discriminability index d’, with scores and standard deviations shown in Table 3. For this analysis, and for all subsequent behavioral results, a 2x2 within-subjects Analysis of Variance (ANOVA) with factors of context (congruent vs. syntactic prose) and ending word type (ambiguous vs. unambiguous) was conducted. Results revealed a significant main effect of context type, $F(1,17) = 11.41, p < .01$, with better memory for words appearing in congruent than in syntactic prose sentences. There was no main effect of ending word type or significant interaction between the two factors ($F$s $< 1$). This overall level of performance is comparable to that in the ERP study using these materials (in which participants were 98% accurate on average; Lee & Federmeier, 2009), and the effect pattern is the same.

Sentence recognition task.

Young adults’ overall accuracy in the sentence recognition task was 83%, which, while lower than that for the word recognition task, still shows that participants were attending to the stimuli and encoding the sentences as a unit. An omnibus ANOVA revealed a main effect of context, $F(1,17) = 17.6, p < .01$, with better memory for congruent sentences. There was no main effect of ending word type, but there was a significant interaction between the two factors, $F(1,17) = 4.82, p < .05$. This interaction could be due to the reading time differences, whereby relatively longer reading times on ambiguous target words in the syntactic prose context (which will be discussed in detail below) may have led to better encoding of those sentences. This
interaction was not present in the previous ERP experiment using these materials (Lee & Federmeier, 2009), in which words were presented at a predetermined rate. Additionally, the overall performance on the sentence recognition task was lower for natural reading than for the corresponding ERP experiment (in which average accuracy on the sentence recognition task was 93%), which is likely explained by the fact that every trial in the current stimulus set contained both a critical and filler sentence, thus doubling the number of sentences presented to participants.

_Eye-Tracking Results_

First fixation durations and gaze durations were collected for the target word as an index of initial processing time. First fixation duration is the length of the reader’s first fixation on a word, whereas gaze duration is the sum of all fixations on the target word before the eyes leave it in either direction. Additionally, we examined two measures of later processing on the ambiguous words. The first is the probability that a regression will be made back to the word from a later point in the sentence at any time after the first pass (regressions in). The second measure is rereading time, which was calculated for each word by subtracting gaze duration from the word’s total reading time, in order to create a metric of how long a word was reread after it was fixated during the first-pass. Note that for this rereading measure, a word was assigned a rereading value of 0 if it was not refixated, in order to capture the probability of refixating target words, which importantly varied across conditions. For all measures, a 2x2 within-subjects ANOVA was conducted with factors of context (congruent vs. syntactic prose) and word type (ambiguous vs. unambiguous), unless otherwise noted.
First fixation.

In light of ERP results showing frontal negativity to the ambiguous words in the syntactic prose sentences beginning as early as 150-200 milliseconds post-stimulus onset, first fixation durations were examined as a measure of initial processing. Target words in this stimulus set were always preceded by a modifier, most often a function word (e.g., “to” or “the”), which provided clear class-disambiguating information. Function words are often skipped in natural reading, with an estimated skipping rate of around 65 percent (Rayner, 1998); in the current dataset, the function words were skipped in 50.5% of cases before readers fixated the target word. However, when readers do fixate the function words, their short average word length means that at least part of the subsequent ambiguous word is likely to also be in the reader’s field of view, as the estimated word identification span is 7-8 characters to the right of fixation for English readers (Rayner, 1998). Since readers’ first apprehension of the target word was thus roughly evenly distributed between fixations to the target word itself and to its preceding modifier, we created a region of interest encompassing both words and analyzed first fixations on this region as a measure of readers’ initial processing of the ambiguous word (see Table 4 for mean first fixation durations). Analyses revealed a significant main effect of context, $F(1,17) = 5.51, p < .05$, indicating that reading times were longer in the syntactic prose than in the congruent context. There was no main effect of word type ($F < 1$), but the interaction between the two factors was significant, $F(1,17) = 7.22, p < .05$. Follow-up t-tests revealed that the 11 ms cost for ambiguous relative to unambiguous words in the syntactic prose context was significant, $t(17) = 2.48, p < .05$, whereas first fixations did not differ between word types in the congruent context, $t(17) = - .89, p = .39$. When first fixations to the modifier and to the target word (with no prior fixations to the modifier) are examined separately, the same numeric pattern is seen
(modifier: $t(17) = 2.08, p = .05$; target word: $t(17) = 1.87, p = .08$; note that each of these comparisons contains roughly half of the number of trials as in the combined region).}

**Gaze duration.**

Gaze durations include all fixations to the target word before the eyes first leave it. Mean gaze durations can be found in Table 5. Analyses showed a significant main effect of context, $F(1,17) = 43.90, p < .001$, with longer gaze durations in syntactic prose sentences. A marginal effect was found for word type $F(1,17) = 3.13, p = .095$, with fixations on ambiguous words being numerically shorter than those to unambiguous words. The interaction between the two factors was not significant, $(F < 1)$.

**Regressions in.**

The next measure of interest is the probability of regressing in to the target region from a later word in the sentence. Since both the target and its modifier contain disambiguating information, this measure will provide a way to capture how much downstream processing was necessary after readers had moved on (see Table 5 for means). Analyses showed a main effect of context, $F(1,17) = 16.68, p < .01$, as young adults were more likely to regress back to the target region in the syntactic prose context. There was no significant effect of word type, $F(1,17) = 2.76, p = .12$ (numerically, there were more regressions in to ambiguous than unambiguous words), and no interaction between context and word type, $F < 1$.

**Rereading time.**

As an additional later measure of processing, we examined the duration of rereading
times on the target region, which was calculated by subtracting the gaze duration from the total time spent reading the region. As previously mentioned, these values include 0 ms rereading times for cases in which neither word in the region was refixated. Since the probability of refixating target words varies across conditions, and calculating rereading time assumes that a word will be refixated, only including cases in which a word was reread will overestimate the actual average rereading times for the words (see Rayner, Slattery, Dreighe, and Liversedge, 2011). As such, this rereading measure was calculated to capture both the duration and probability of rereading the target words in a single measure. Average rereading times are listed in Table 5. Analyses revealed a significant main effect of context, $F(1,17) = 20.35, p < .01$, indicating that readers spent more time rereading the words in the syntactic prose context. There was also a significant effect of word type, $F(1,17) = 7.03, p < .05$, indicating that readers spent more time rereading the ambiguous compared to unambiguous words overall. The interaction between the two factors was not significant, $F(1,17) = 2.07, p = .17$.

Discussion

Behavioral measures were used to ensure that participants would be motivated to pay attention to the individual words that they were reading and to try to derive a coherent meaning for each sentence. The results confirm that participants indeed attended to the stimuli, both at the level of individual words and at the message level. The effects of context indicate that the addition of coherent meaning to syntactic structure aided memory performance both on short-term single word recall and longer-term entire-sentence recall, a pattern that replicates that seen in Lee and Federmeier’s (2009) corresponding ERP experiment. However, different from the pattern seen when these stimuli were encountered with the fixed presentation rate used for ERP
recordings, the natural reading results indicate that young participants choose to spend more time reading syntactic prose sentences that contain ambiguous words than those without ambiguous words, contributing to better memory for these sentences overall, although this effect is not strong enough to override the benefits of coherent semantics.

Patterns of eye fixations on the critical region (ambiguous and unambiguous target words and their preceding modifiers) show the same pattern as observed in ERP measures. In syntactic prose sentences, participants’ first fixations to the target region were longer on average for ambiguous than for unambiguous words. This ambiguity effect, however, disappeared in the context of congruent semantic information. ERP measures consistently show an enhanced frontal negativity for ambiguous compared to unambiguous words in a variety of contexts that contain only syntactic disambiguating information (Federmeier et al., 2000; Lee & Federmeier, 2006, 2009). The effect, however, was eliminated in the presence of biasing semantic information in the ERP study employing the same sentences as those we are using here. The similarity in the pattern across conditions, as well as the overlap in the timing of these effects (the frontal negativity begins prior to 200 ms post-stimulus onset and the first fixation durations were in the 200-250 ms range), suggests that these two effects may share a common source.

Later gaze measures consistently reveal costs associated with reading in the syntactic prose sentences as compared with the congruent sentences, with longer gaze durations, more regressions in, and longer rereading times for syntactic prose sentences, regardless of whether they contain an ambiguous or unambiguous target word. As the syntactic prose sentences are semantically incoherent, these costs are not surprising, and analogous effects are seen with ERPs, including larger N400 effects in syntactic prose than in congruent sentences, pointing to more difficult semantic processing. Rereading times were also longer for ambiguous than
unambiguous words across context types, suggesting that when readers have control over their intake of information (different from the corresponding ERP experiment), they tend to spend more time when they go back to ambiguous words, perhaps reflecting cases in which these items were not fully disambiguated during the first pass.
Experiment 2: Older Adults

The results from the younger adults show that effects seen in the ERP findings linked to effortful selection processes have parallels in first fixation times, both of which come online around 200 ms of first encountering an ambiguous word in the absence of coherent semantics. These parallel effects suggest that inhibitory processes used to suppress contextually inappropriate meanings may also slow the eyes during natural reading. A stronger test of this assumption would come from examining the reading patterns of older adults using these same materials. Recall that Lee and Federmeier (2011) found that the frontal negativity effects were absent in older adults as a group, although could be seen in older adults with high verbal fluency. If the two effects do indeed share a source, we might expect for the first fixation effects to be reduced or absent in older adults as a group, but it could also show sensitivity to verbal fluency as well – a prediction we will examine next.

Methods

Materials

The materials used were the same as those used for the young adults.

Participants

Eighteen older adults (5 men; mean age 69.5 years; range 62-83 years) participated in the eye-tracking experiment for cash payment. All participants were right-handed as assessed by the Edinburgh inventory (Oldfield, 1971), eight reported having at least one left-handed family member. All were also monolingual speakers of English, with no consistent exposure to other languages before age 5. Participants had no history of neurological/psychiatric disorders or brain
damage. We conducted a modified, combined version of the Montreal Cognitive Assessment (MoCA) and the Mini Mental State Exam (MMSE) to screen participants for cognitive impairments. The average score for the MoCA items was 26.31 out of 29 possible points ($SD = 1.82$; range 22-29), and the average score for the MMSE items was 54 of a possible 57 points ($SD = 2.28$; range 50-57), for a combined overall average of 80.3 out of a possible 86 points ($SD = 3.52$; range 74-85).

**Procedure**

The procedure was the same as that used for the young adults. Following the eye-tracking portion, the same neuropsychological tests were administered to the older adults. For the reading span test, the average set size was 2.5 ($SD = .059$; range 2-4), and the average total number of words recalled was 51.2 ($SD = 13.8$; range 35-78), which is highly overlapping with the scores from Lee and Federmeier (2011). In the Hayling test, the average number of correct congruent responses (out of a total of 24 trials) was 23.9 ($SD = 0.25$; range 23-24), while the number of correct anomalous responses was 21 ($SD = 4.50$; range 10-24). For the verbal fluency tests, participants generated, on average, 48.6 words in the letter fluency test ($SD = 13.5$; range 26-70), and 65.2 words in the category fluency test ($SD = 13.0$; range 45-101), for an average of 113.8 total words generated ($SD = 23.2$; range 71-169). Again, these ranges are very comparable to those from the older adults in Lee and Federmeier, 2011).
Data Analysis

The same criteria for including fixations used for young adults were also used for the older adults. The total number of fixations included in each condition of interest can be found in Table 2.

Results

Behavioral Results

Word recognition task.

Overall accuracy on the word recognition task for older adults was 92%, and memory performance in each condition was again analyzed using the d’ index (see Table 3 for means). Results showed a main effect of context, $F(1,17) = 39.98, p < .01$, with better word recognition in congruent sentences than in syntactic prose, but no main effect of word type nor interaction between the two factors ($F$’s < 1). This level of performance is slightly lower than the 98% accuracy seen in Lee and Federmeier’s (2011) ERP experiment, although the pattern of effects is the same across experiments.

The older adults’ performance was also numerically lower than that of the young adults. To test for significant differences between the groups, an omnibus ANOVA was run with the between-subjects factor of age (young and old), and within-subject factors of context (congruent vs. syntactic prose) and ending word type (ambiguous vs. unambiguous). The test showed a significant main effect of context, $F(1,34) = 48.91, p < .01$, but no reliable effect of ending word type ($F < 1$) or age $F(1,34) = 2.42, p = .13$. However, age significantly interacted with context, $F(1,34) = 6.65, p < .05$, indicating that although both groups demonstrated poorer memory
performance for words appearing in the syntactic prose context, this deficit was larger for the older adults.

**Sentence recognition task.**

Overall accuracy in the sentence recognition task for older adults was 82%. Analyses of d’ scores (listed in Table 3) showed a main effect of context, $F(1,17) = 7.24, p < .05$, with reduced memory for syntactic prose than for congruent sentences. There was no main effect of word type nor interaction between the two factors ($F$s < 1). Overall accuracy was again slightly lower than the 89% observed by Lee and Federmeier (2011), although, as previously mentioned, the ERP version contained half the number of sentences overall.

As with the word recognition task, older adults’ performance on the sentence recognition task was slightly lower than that of the young adults in Experiment 1. To directly compare performance, an omnibus ANOVA was run with the between-subjects factor of age (young and old), and within-subject factors of context (congruent vs. syntactic prose) and ending word type (ambiguous vs. unambiguous). The test showed a significant main effect of context, $F(1,34) = 63.51, p < .01$, but no reliable effect of ending word type or age ($F$s < 1). However, age showed a marginal interaction with context, $F(1,34) = 2.92, p = .097$, indicating again that older adults were more affected by the difficulty of the syntactic prose sentences than were younger adults.

**Eye-Tracking Results**

**First fixation.**

Like the younger adults, the older adults skipped the modifier directly preceding the target word 50.4% of the time, creating a situation in which their first apprehension of the target
word is distributed almost evenly between fixations to the modifier and fixations to the target word. As such, first fixations for the older adults were also examined for the target region (see Table 4 for means). Results revealed a main effect of context, \( F(1,17) = 6.75, p < .05 \), but no effect of word type or interaction (\( F's < 1 \)). These results indicate that first fixation durations were longer in the syntactic prose context, but, importantly, that they did not differ between ambiguous and unambiguous words. Similar analyses conducted on the target and modifiers separately produced very similar results, with longer first fixations in the syntax-only contexts but no main effects or interactions with word type.

**Gaze duration.**

As with the young adults, gaze durations were examined for target words (see Table 5 for means). Results revealed a main effect of context, \( F(1,17) =33.75, p < .01 \), with longer gaze durations in syntactic prose sentences. There was also a main effect of word type, \( F(1,17) =8.73, p < .01 \), arising from longer gaze durations to unambiguous than to ambiguous words overall. However, there was no interaction between the two factors (\( F < 1 \)).

**Regressions in.**

The probability of regressions in to the target region was examined next (see Table 5). Analyses showed a main effect of context, \( F(1,17) =9.95, p < .01 \), but no main effect of word type (\( F < 1 \)) or interaction between the two factors, \( F(1,17) = 2.15, p = .16 \). Older adults are more likely to regress in to the target word in the syntactic prose context, but, as for younger adults, this effect was not modulated by word type.
**Rereading time.**

Finally, analyses of rereading times (means in Table 5) for the target region revealed a significant main effect of context, $F(1,17)=12.82, p < .01$, a main effect of word type, $F(1,17)=11.86, p < .01$, as well as an interaction, $F(1,17)=9.87, p < .01$. Follow-up comparisons show that the interaction is driven by the significant 70 ms difference in rereading times between the ambiguous and unambiguous targets in the syntactic prose condition, $t(17) = 3.62, p < .01$, whereas the 2 ms difference between word types in the congruent context is not reliable, $t(17) = .20, p = .84$. Therefore, like the younger adults, older adults do more rereading in syntactic prose contexts and also of ambiguous words. However, different from the younger adults, the older adults show a pattern in which they selectively spend more time rereading ambiguous words than unambiguous words in the syntactic prose contexts -- a pattern that is eliminated in the congruent sentences. Thus, the pattern observed on the frontal negativity and in first fixation times for the younger adults is seen instead in rereading times for older adults as a group.

**Individual Differences Analyses**

In the previous ERP study using the same materials, Lee and Federmeier (2011) found that among older adults there was a significant relationship between the size of the frontal negativity effect and verbal fluency, such that higher verbal fluency scores were associated with a larger frontal negativity effect. Given the similarities of the frontal negativity and the first fixation effects in terms of timing and sensitivity to context and age, it seems likely that they are related, perhaps indexing the same underlying process. If this is the case, then older adults with high verbal fluency should exhibit the first fixation effect, whereas those with low verbal fluency would not. This individual difference might also hold for young adults; Lee and Federmeier did
not collect fluency scores for their young adults, so it is not possible to determine whether individual differences might also have obtained for the younger adults’ ERP effects. In our sample, verbal fluency scores were well matched between younger and older adults: young adults had a mean fluency of 70.2 with a range of 51-114 and older adults had a mean fluency of 64.2 with a range from 45-101. Fluency did not differ as a function of age, $t(32) = -1.26, p = .22$.

Therefore, to better understand the relationship between eye-movement patterns and fluency, eye movement measures were regressed against verbal fluency measures for both age groups together. To examine first fixation effects, a measure of ambiguity cost in the syntactic prose condition was calculated for all participants by subtracting first fixation durations to the target region for unambiguous from ambiguous words (producing a positive value when a participant had longer first fixations on ambiguous words). Overall fluency was marginally correlated with the ambiguity cost, $r = .30, p = .08$, and category fluency in particular was significantly correlated, $r = .34, p < .05$, with participants who were able to produce more words showing larger ambiguity costs (Figure 1). The other subcomponent of verbal fluency, FAS fluency, was not correlated with the ambiguity cost, $r = .17, p = .33$.

Furthermore, since the ambiguity cost was expressed in the older adults as longer rereading times on the ambiguous words, we wanted to explore whether this cost was also correlated with verbal fluency, or whether it was simply an expression of group differences regardless of individual differences. A second measure of ambiguity cost was calculated for all participants by subtracting the rereading times on the unambiguous words from ambiguous words in the syntactic prose condition (again producing a positive value when a participant has longer rereading times for the ambiguous words). Overall fluency showed a marginal negative correlation with rereading cost, $r = - .29, p = .097$, and again, category fluency had a significant
negative correlation, $r = - .34, p < .05$, with participants who produced fewer words showing larger ambiguity costs in rereading times (Figure 2). As before, the other subcomponent of verbal fluency, FAS fluency, was not correlated with the rereading ambiguity costs, $r = -.16, p = .37$.

Discussion

The behavioral results show that, as was true for younger adults, older adults’ memory performance was significantly better for both single words and entire sentences appearing in the congruent contexts. Additionally, although there were no significant main effects of age, interactions between age and context type suggest that the lack of coherent semantics is more detrimental to older adults’ ability to remember words and sentences, after both short and longer delays. This interaction was not present in the ERP study, which could possibly be explained by the fact that the current study included double the number of sentences, with both critical and filler sentences in every trial, while the ERP study only included the critical sentences. It is possible, then, that the additional material included in the current study was more taxing on older adults’ memory, thus magnifying the memory deficits caused by the lack of coherent semantics.

Critically, as predicted, the eye-tracking results revealed that older adults do not exhibit inflated first fixation durations for ambiguous words in the syntax-only context. This finding strengthens the tie between the first fixation ambiguity effect seen in the young adults and the ERP frontal negativity that has been seen under the same conditions with these same stimuli (Lee & Federmeier, 2009), as both effects are absent in older adults as a group (Lee & Federmeier, 2011). Similar to the pattern seen for the young, older adults’ gaze durations are shorter for words in congruent contexts as well as for ambiguous words overall, and they show a higher probability of regressing in to both word types in the syntactic prose context.
Interestingly, and different from younger participants, older adults spend more time rereading ambiguous words in the syntactic prose contexts. The pattern seen on first fixations for young adults thus appears on a much later reading measure in older adults, suggesting that older adults are impaired at recruiting resources important for meaning selection during their initial reading, necessitating that they return to the ambiguous word for further processing.

Further evidence for this trade-off between first fixation and rereading effects can be seen in the pattern of individual differences. Lee and Federmeier (2011) found that although older adults as a group failed to elicit the frontal negativity effect, a subset of older adults with higher verbal fluency showed the young-like pattern. We regressed the size of the ambiguity effect on first fixations with verbal fluency, and found that -- for both age groups -- higher category fluency scores indeed predicted larger first fixation effects. At the same time, fluency was negatively correlated with ambiguity effects on rereading. Thus, at the individual level as well as at the group level (as a function of age), readers exhibit a trade-off between slowing down during their first apprehension of ambiguous words in contexts demanding effortful meaning selection, or, instead, spending more time rereading those words after the first pass through the text.
General Discussion

The current study investigated how young and older adults use semantic and syntactic context information to resolve the ambiguity associated with noun/verb homographs (e.g. *park*) during natural reading. Overall results showed that when only syntactic information was available, young adults exhibited inflated first fixation durations on their first apprehension of the ambiguous words, whereas older adults as a group did not. The presence of coherent semantic information eliminated this cost for young participants. These findings parallel previous ERP work by Lee and Federmeier (2009, 2011), which found sustained frontal negativity elicited by the ambiguous words in the syntactic prose context for younger, but not older, adults -- an effect that was also eliminated by coherent semantics. The fact that the first fixation and frontal negativity effects arise in the same conditions and age groups and come online in the same time window, between 150-250 ms after first apprehending the target word, suggests that there is overlap in the process(es) that underlie these effects.

Lee and Federmeier (2009, 2011) posited that the frontal negativity indexes fronto-temporally mediated meaning selection processes that are necessary in the absence of coherent semantic information, which likely involve suppression of the word’s context-inappropriate meaning. A follow-up study from Lee and Federmeier (in press) was conducted to investigate how the frontal negativity effect impacts downstream processing in order to better understand its functional role. To do so, they embedded NV homographs in semantically neutral but syntactically constraining sentences. The homographs were immediately followed by a prepositional phrase whose head noun was more plausible for one interpretation of the homograph than the other. For example, the sentence, *Ben tried the duck in the dish prepared by the famous chef*, is plausible, while the sentence, *Ben tried to duck in the dish prepared by the*
famous chef, is implausible. Importantly, both sentences could be completed plausibly up until the bolded noun (e.g. Ben tried to duck in the alley to avoid the paparazzi), which is the head noun of the prepositional phrase. ERPs were observed to the head noun as a probe of the outcome of ambiguity resolution. Their results showed that young adults elicited a frontal negativity that began with the onset of the NV homograph and was sustained over the next two words until readers received the head noun of the prepositional phrase, at which point they showed a clear N400 plausibility effect (i.e., reduced N400 for plausible relative to implausible nouns). The young adults showed this effect regardless of whether the context picked out the dominant or subordinate sense of the word. Since there was only downstream activation for nouns that were plausible for the context-appropriate meaning of the target word, it suggests that the frontal negativity indexed the young adults’ ability to successfully suppress the context-inappropriate meaning. We postulate that this suppression also causes the first fixation effects by generating an inhibition signal that slows the eyes when readers first apprehend those words.

It is curious to note that our first fixation findings conflict those from a previous eye-tracking study looking at how readers resolve NV homographs. Folk & Morris (2003) found that in semantically neutral but syntactically constraining sentences, gaze durations and spillover times did not differ between NV homographs and their unambiguous controls, which they cited as evidence that syntactic information is sufficient to resolve the ambiguity associated with NV homographs. There is one caveat to their findings, however: their materials always picked out the noun meaning of the NV homographs. This opens up the possibility that readers in their study implicitly learned this statistical probability throughout the experiment and automatically suppressed the homograph’s verb interpretation, effectively eliminating the need to activate top-down selection mechanisms. Unfortunately, Folk and Morris (2003) did not report first fixation
durations, which is where the effects were present in our young adult population, nor did they separate instances in which readers first fixated the function word the, which preceded all of their ambiguous words, as in the present study. That neither study found effects on gaze durations to the noun/verb homographs might indicate that these effects are quickly resolved, or that by the time readers refixate the word on gaze duration, a secondary process other than semantic access (i.e. text integration, syntactic processing) may take over control of the eye movement program. Without being able to examine their first fixation effects, we are unable to conclusively determine if our findings actually contradict those of Folk and Morris (2003), or if ambiguity effects might truly be present on their first fixation durations, but are masked by the effects of preview. However, we can safely say that our data is inconsistent with their claim that syntactic constraints alone can eliminate the ambiguity associated with noun/verb homographs.

In addition to the similarity between the ERP frontal negativity and the first fixation effects in the present study, other aspects of the eye-tracking data mirrored ERP data patterns as well. Lee and Federmeier (2009) observed a general reduction in N400 amplitude (250-500 ms) in the congruent context compared to the syntactic prose context for both ambiguous and unambiguous words (cf., Van Petten & Kutas, 1990). The reduction in N400 amplitude likely reflects the build-up of message-level semantics in the congruent – but not syntactic prose – contexts, which eased word processing. Similarly, in the eye-tracking study, there is an overall decrease in gaze durations to the target words in the congruent context relative to the syntactic prose context. This effect probably reflects general facilitation of lexical access and/or meaning integration when the sentence provides supportive semantic and syntactic context. This same pattern of facilitation is also present on the regressions in measure, as readers were less likely to make a regression in to the target word in the congruent context than in the syntactic prose, again
likely reflecting easier processing in the congruent context. Together, these findings suggest that
the addition of coherent semantics to syntactically well-formed sentences generally facilitates the
processing of words in that context, and that this facilitation is evident in both the brain and
behavioral response to these sentences.

Although the later eye gaze measures mirrored the general pattern of context effects on
the N400, additional effects of ambiguity on the N400 in Lee & Federmeier (2009) were not
found in eye movement patterns in the present study. Lee and Federmeier (2009) found that in
the congruent context, the N400 elicited by the unambiguous words showed a greater reduction
than that seen to the ambiguous words, even though they were matched for cloze probability
(i.e., predictability). In a second experiment, this pattern was shown to be specific to cases in
which the context picked out the subordinate meaning of the ambiguous words, and it was
hypothesized to reflect residual activation of dominant meaning features. These N400 ambiguity
effects were not seen in the gaze duration data in the present experiment. Furthermore, within the
two contexts, readers were equally likely to make a regression to the target word, regardless of
whether it was ambiguous or unambiguous. The fact that neither gaze durations nor probability
of regression in showed ambiguity effects like those seen on the N400 in congruent contexts is
consonant with Lee and Federmeier’s (2009) hypothesis that the N400 pattern indexes residual
activation of the alternative meaning within semantic memory, which is resolved without the
need to recruit additional neural resources – and, thus, perhaps, without concomitant behavioral
consequences.

A different pattern of eye movement results emerges for the older adults. It has been
consistently found that older adults, as a group, also fail to elicit the frontal negativity when they
encounter NV homographs with clearly disambiguating syntactic, but not semantic, constraints
(Lee and Federmeier, 2011; in press). Interestingly, Lee and Federmeier (in press) have shown that the failure to elicit the frontal negativity seems to indicate a failure to select the context-inappropriate meaning of the ambiguous word. They found that after older adults viewed NV homographs preceded by a semantically neutral context, and failed to elicit the frontal negativity, they later showed N400 plausibility effects to the head noun of the following prepositional phrase only for nouns consistent with the dominant meaning of the ambiguous word. Thus, it seems they selected a meaning based on dominance rather than utilizing the syntactic cues.

The older adults did not show the first fixation effect in the syntactic prose context, which was in line with our predictions based on the previous ERP findings. This failure to recruit the selection mechanisms also means that the older adult readers did not spend more time on the ambiguous words in the prose context, relative to the unambiguous words (like the young adults did), and thus may not have had the opportunity to spend more time processing—and disambiguating—the NV homographs. In ERPs, when presentation rates are fixed and there is no opportunity to look back, this seems to result in comprehension problems that may be difficult to overcome. However, with eye-tracking we have the ability to observe downstream processing consequences after readers have moved on from the ambiguous words, since readers are free to move their eyes back in the text to areas which may have caused difficulties. Interestingly, the older adults as a group spent more time rereading the ambiguous words in the syntax-only context, an effect not present in the young adults. This finding suggests that the older adults did not initially select a meaning for the ambiguous words, and that this failure resulted in the need to later return to these words.

Beyond the effects of age, individual differences played a key role in determining reading behaviors. Motivated by Lee and Federmeier’s (2011) finding that older adults with high verbal
fluency showed a young-like pattern of frontal negativity, we also discovered significant
correlations between verbal fluency and ambiguity effects that reveal striking similarities across
the two age groups. High verbal fluency readers showed larger first fixation ambiguity effects
than low verbal fluency readers, a pattern that held true for both age groups. Verbal fluency has
been linked to the integrity of frontal cortical areas and, more specifically, to the efficacy of
fronto-temporal circuits. One’s verbal fluency may therefore reflect the speed and/or efficacy of
the transmission of incoming sensory information to frontal areas important for selection and eye
movement control, making it a useful predictor of the first fixation ambiguity effects.
Furthermore, there is an inverse relationship between verbal fluency and rereading times, such
that readers with low verbal fluency spend more time rereading the ambiguous words in the
syntactic prose context. This correlation suggests that the low fluency readers must spend more
time rereading the ambiguous words in order to resolve meaning ambiguity that was not resolved
on their first pass through the sentence. Taken in tandem, these patterns demonstrate an
interesting trade-off between these two effects: high fluency readers tend to show larger initial,
and smaller later, effects, whereas low fluency readers show smaller initial, but larger later,
effects.

In order to better understand the nature of the relationship between verbal fluency and
ambiguity effects, the two age groups were divided into high- and low-verbal fluency subgroups,
and reading time measures were examined to the target region as a function of both age and
verbal fluency group. Mean first fixation durations for the target region in the syntactic prose
context are shown in Figure 3 (see Table 6 for values). Examining the numerical patterns of the
four groups, the largest ambiguity effect on the target region is seen for the high fluency young
adults, and is present but smaller for both the low fluency young and the high fluency older
adults. In contrast, the low fluency older adults fail to show this ambiguity cost, and rather show a slight benefit for the ambiguous words. If each word of the target region is examined separately, a slightly different pattern of effects emerges. The first fixation ambiguity effect on the target word alone (without a fixation to the modifier) is clearly present for only the high fluency young adults (Figure 4); reading times do not differ for ambiguous and unambiguous words in any of the other three groups. Interestingly, when first fixations to the modifier (pre-target) are examined (Figure 5), the effect is present in both the high and low fluency young adults, as well as the high-fluency older adults (although only for the first of multiple fixations on the word; see Reingold, Yang & Rayner, 2010), and is slightly reversed in the low fluency older adults.

To examine the downstream effects of ambiguity, regressions in to the target region in the syntactic prose context are considered next. As can been seen in Figure 6, both the low fluency young adults and the high fluency older adults show an ambiguity effect on this measure. On the other hand, the high fluency young and low fluency older adults each show a roughly equal tendency to refixate both word types in the syntactic prose context (although the older adults were roughly 1.5 times more likely to do so). Finally, rereading times for all groups in the syntactic prose context can be found in Figure 7. The low fluency older adults show the largest ambiguity effect for this measures, while both the high fluency older and low fluency young adults each show rereading effects of roughly equal magnitude. Interestingly, the high fluency young adults are the only readers who do not show a tendency to reread the ambiguous words in the syntactic prose context.

The pattern observed across the four groups further demonstrates a trade-off between first fixation and downstream costs. This dichotomy is most clearly seen in the two most extreme
groups: the high verbal fluency young adults and the low verbal fluency older adults. The high fluency young exhibit clear first fixation effects, suggesting that they can engage their selection mechanisms both quickly and effectively. They are the only group to show this effect on their first look to the target word itself, and also the only ones who show no further processing costs on the ambiguous words. This pattern of early, but not late, effects suggests that the initial meaning selection process was successful for these readers.

Effect patterns in the low fluency older adults are nearly the opposite of those seen for the high fluency young. They do not exhibit any first fixation costs, suggesting they do not initially select a meaning, but rather spend significantly more time rereading the ambiguous target region. This pattern highlights the striking trade-off between the first fixation and rereading effects: readers either slow down initially to select a meaning, or reread the word later to resolve the ambiguity.

On the other hand, the low fluency young and high fluency older adults exhibit remarkably similar patterns to each other for every measure analyzed, which diverge in important ways from the two groups already discussed. Both the low fluency young and high fluency older adults show ambiguity effects on first fixation when those fixations are to the modifier, but not when they land directly on the target. Considering the length of the function words (typically 2-3 letters), these readers were very likely able to foveate the target word simultaneously with the function word in the cases where they exhibited the effect, since the range of word identification extends 7-8 characters to the right of fixation (Rayner, 1998). This pattern suggests that these two groups were only able to recognize the ambiguity and bring their selection mechanisms online when they received both words together. This distinction is important, because receiving the function and target words together makes clear the context-
appropriate sense. When readers skip the function word and look directly to the target ambiguous word, it is unclear if they already received information about the function word from a previous fixation, and if so, whether they can quickly integrate this information across saccades for their use in interpreting the target. Their lack of ambiguity effects in cases where they looked directly to the target word suggests that they may not have utilized the syntactically disambiguating information from the function word and may have instead either activated both meanings of the word or selected based on meaning frequency.

In terms of their downstream processing costs, both groups show a significantly higher proportion of regressions in to the ambiguous, compared to unambiguous, target region. Not only is the ambiguity effect of a similar magnitude for both young and older readers (6.0% and 6.3%, respectively), but also the actual numeric values for these two groups fall within 2% range for each word type. Thus, these groups are not only qualitatively but also quantitatively similar in their probability of refixating the target region. Both groups show very similar patterns in their rereading times on the ambiguous target region as well. The fact that these two groups show both early and late effects gives us insight into the efficiency of their ambiguity resolution processes. Even though both groups showed the first fixation effect, it was only in a limited number of cases and was weaker than the effect in the high fluency young adults. Furthermore, they were seemingly unable to fully resolve the ambiguity since they still returned to the ambiguous words later, although their rereading effects were weaker than those for the low fluency older adults. Judging by these patterns, the low fluency young and high fluency older adults appear less efficient at engaging their selection mechanisms when necessary, and even the recruitment of these mechanisms is not sufficient to fully resolve the ambiguity in all cases.
These findings have interesting implications for the interpretation of the ERP results from Lee and Federmeier (2009, 2011). The differential pattern of results found in the two methodologies highlights the nuanced findings that can emerge when the same set of stimuli are used in each measure separately. Recall that in the ERP studies, sentences are presented one word at a time, for a fixed amount of time per word. In this method, participants have no control over the timing or order in which they take in the information, and importantly, cannot view a word again after it has left the screen. When stimuli are presented this way, both the high and low fluency young adults have the necessary resources available to engage their top-down selection mechanisms online, thus eliciting the frontal negativity. However, this may not be their typical ambiguity resolution strategy, especially for the low fluency readers. When given the ability to freely read the sentences in the eye-tracking paradigm, the low fluency young adults only initially recruit the selection mechanisms in a limited number of cases, when they received the function and target words in the same fixation. It might be the case for these readers that their typical strategies in natural reading, wherein function words are often skipped, may actually be disadvantageous for them, since they seem less able to make use of the critically disambiguating function word information when it is skipped. When they are given the function word in the ERP study -- or when they happen to land on it during natural reading – the low fluency young readers seem better able to make use of first pass ambiguity resolution strategies.

This is different from what seems to be happening for the older adults. Since the older adults as a group do not exhibit the frontal negativity or first fixation effects, it seems that they are less able to rapidly recruit selection mechanisms. Even high fluency older adults who do elicit the first fixation effect in limited conditions (and who elicit some frontal negativity as well), show a tendency for refixating and rereading the ambiguous words later, suggesting that
they may be unable to fully suppress the context-inappropriate meaning of the ambiguous word. The low fluency older adults, whose resources are presumably even more reduced, do not show the first fixation effects in even limited conditions, and also show the largest rereading effects. This marks an important age-related distinction in the trade-off between resource availability and preferred reading strategy. While both high and low fluency younger adults have the resources to recruit the selection mechanisms in the ERP study when they have no other strategy option, the older adults’ reduced cognitive resources hinder their ability to do so, even when it is their only option for resolving the word’s meaning. Older adults with high verbal fluency appear to have greater resource capacity than the low fluency, but this protective effect of verbal fluency cannot fully maintain their processing efficiency to the level of the high fluency young. Thus, the ERP effects can be thought of as showcasing which processes readers can engage when they cannot make strategic processing choices, whereas the eye-tracking measures give insight into an individuals’ typical strategy when they have the ability to move their eyes over the text at will.

In summary, the current study found interesting parallel effects when the same materials were used separately in the ERP and eye-tracking paradigms. Both methodologies found that young adults exhibit initial ambiguity effects when they encounter noun/verb homographs in syntactic prose sentences, thought to be associated with the recruitment of fronto-temporally mediated meaning selection mechanisms necessary when semantic cues are absent. Older adults as a group do not exhibit this effect in either methodology, but rather reread the ambiguous words more in the same context, likely to compensate for their failure to initially recruit these mechanisms and select a meaning. These age-related differences were further modulated by verbal fluency, such that high fluency young adults showed the clearest initial effects, low fluency older adults showed the clearest rereading effects, and the low fluency young and high
fluency older adults showed limited initial and weaker rereading effects. These results suggest a clear age-related decline in the efficacy of these top-down meaning selection mechanisms, which higher verbal fluency can partially protect against. They also highlight the importance of comparing effects across modalities, by showing that while all older adults may not exhibit young-like patterns of ambiguity resolution, each group has adopted compensatory strategies to aid their lexical ambiguity resolution, which would have gone unnoticed in the ERP studies alone.
Table 1

*Example sentences from critical contexts.*

<table>
<thead>
<tr>
<th>Context Type</th>
<th>Example Sentence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congruent</td>
<td>On many freeways now, you can just use a pass instead of having to stop to pay the toll. This keeps traffic moving quickly.</td>
</tr>
<tr>
<td>Syntactic Prose</td>
<td>On many books now, you can just understand a room instead of having to walk to find the toll. This keeps psychology waiting quickly.</td>
</tr>
</tbody>
</table>
Table 2

*Total number of first fixations in conditions of interest.*

<table>
<thead>
<tr>
<th>Context</th>
<th>Word Type</th>
<th>Target (No modifier)</th>
<th>Modifier (Pre-target)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Young</td>
<td>Old</td>
</tr>
<tr>
<td>Congruent</td>
<td>Ambiguous</td>
<td>297</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>Unambiguous</td>
<td>321</td>
<td>239</td>
</tr>
<tr>
<td>Syntactic Prose</td>
<td>Ambiguous</td>
<td>261</td>
<td>193</td>
</tr>
<tr>
<td></td>
<td>Unambiguous</td>
<td>305</td>
<td>221</td>
</tr>
</tbody>
</table>

Note: *Target (No modifier)* refers to the sum total of cases in which the first fixation to the target region was to the target word. *Modifier (pre-target)* represents the sum total of cases in which the first fixation to the target region was to the modifier.
Table 3

*D-prime scores (and standard deviations) for word and sentence recognition tasks.*

<table>
<thead>
<tr>
<th>Context</th>
<th>Word Type</th>
<th>Word</th>
<th></th>
<th>Sentence</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Young</td>
<td>Old</td>
<td>Young</td>
<td>Old</td>
</tr>
<tr>
<td>Congruent</td>
<td>Ambiguous</td>
<td>2.83 (.29)</td>
<td>2.78 (.27)</td>
<td>2.24 (.56)</td>
<td>2.40 (.42)</td>
</tr>
<tr>
<td></td>
<td>Unambiguous</td>
<td>2.76 (.28)</td>
<td>2.75 (.35)</td>
<td>2.31 (.54)</td>
<td>2.39 (.46)</td>
</tr>
<tr>
<td>Syntactic Prose</td>
<td>Ambiguous</td>
<td>2.60 (.41)</td>
<td>2.34 (.48)</td>
<td>1.81 (.76)</td>
<td>1.52 (.86)</td>
</tr>
<tr>
<td></td>
<td>Unambiguous</td>
<td>2.57 (.36)</td>
<td>2.32 (.37)</td>
<td>1.59 (.48)</td>
<td>1.50 (.65)</td>
</tr>
</tbody>
</table>
Table 4

*First fixation durations for young and older adults*

<table>
<thead>
<tr>
<th>Context</th>
<th>Word Type</th>
<th>Target Region (No modifier)</th>
<th>Target Region (Pre-target)</th>
<th>Target Region (Post-modifier)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Young Old</td>
<td>Young Old</td>
<td>Young Old</td>
</tr>
<tr>
<td>Congruent</td>
<td>Ambiguous</td>
<td>222</td>
<td>251</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>Unambiguous</td>
<td>227</td>
<td>251</td>
<td>237</td>
</tr>
<tr>
<td>Syntactic Prose</td>
<td>Ambiguous</td>
<td>237*</td>
<td>265</td>
<td>252†</td>
</tr>
<tr>
<td></td>
<td>Unambiguous</td>
<td>226</td>
<td>263</td>
<td>240</td>
</tr>
</tbody>
</table>

Note: * indicates $p < .05$; † indicates $.05 < p < .08$ (for within-context comparison between ambiguous and unambiguous). Target (no modifier) refers to cases in which the first fixation in the target region was to the target word; modifier (pre-target) refers to cases in which the first fixation in the target region was to the modifier; and target (post-modifier) refers to cases in which the first fixation to the target word was directly preceded by a look to the modifier.
Table 5

Remaining reading time measures for both young and older adults

<table>
<thead>
<tr>
<th>Context</th>
<th>Word Type</th>
<th>Gaze Duration</th>
<th>Regressions In</th>
<th>Rereading Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target Word</td>
<td>Young (ms)</td>
<td>Old (ms)</td>
<td>Young (ms)</td>
</tr>
<tr>
<td></td>
<td>Target Region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congruent</td>
<td>Ambiguous</td>
<td>250</td>
<td>303</td>
<td>.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>267†</td>
<td>326**</td>
<td>.16</td>
</tr>
<tr>
<td></td>
<td>Unambiguous</td>
<td>294</td>
<td>354</td>
<td>.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>301</td>
<td>365</td>
<td>.21</td>
</tr>
<tr>
<td>Syntactic Prose</td>
<td>Ambiguous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>294</td>
<td>354</td>
<td>.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>301</td>
<td>365</td>
<td>.21</td>
</tr>
</tbody>
</table>

Note: * indicates $p < .05$; † indicates $.05 < p < .08$ (for within-context comparison between ambiguous and unambiguous)
Table 6

Reading time measures divided by verbal fluency groups for both young and older adults in syntactic prose context only

<table>
<thead>
<tr>
<th>Word Type</th>
<th>First Fixation</th>
<th>Regressions</th>
<th>Rereading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target Region</td>
<td>Modifier: Pre-Target</td>
<td>Region</td>
</tr>
<tr>
<td></td>
<td>Target: No Modifier</td>
<td>Region</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Young Old</td>
<td>Young Old</td>
<td>Young Old</td>
</tr>
<tr>
<td>Low Verbal Fluency</td>
<td>231 261</td>
<td>243 276</td>
<td>228 245</td>
</tr>
<tr>
<td></td>
<td>225 267</td>
<td>239 274</td>
<td>210 255</td>
</tr>
<tr>
<td>High Verbal Fluency</td>
<td>242 273</td>
<td>261 287</td>
<td>227 271</td>
</tr>
<tr>
<td></td>
<td>228 265</td>
<td>241 289</td>
<td>214 233</td>
</tr>
</tbody>
</table>
Figure 1. Scatterplot of the correlation between category verbal fluency and first fixation ambiguity effects (measured by subtracting first fixations to unambiguous words from those to ambiguous words) for both young and older adults.
Figure 2. Scatterplot of the correlation between category fluency and ambiguity effects on rereading times (calculated by subtracting rereading times on unambiguous words from those to ambiguous words) for young and older adults.
Figure 3. First fixation durations on the target region, in the syntactic prose contexts only, as a function of both age and verbal fluency group. (AA = Ambiguous Words, UW = Unambiguous Words)
Figure 4. First fixation durations on the target word (not preceded by a fixation to the modifier), in the syntactic prose contexts only, as a function of both age and verbal fluency group. (AA = Ambiguous Words, UW = Unambiguous Words)
Figure 5. First fixation durations on the modifier (pre-target fixation), in the syntactic prose contexts only, as a function of both age and verbal fluency group. (AA = Ambiguous Words, UW = Unambiguous Words)
Figure 6. Probability of regressions in to the target region in the syntactic prose contexts only, as a function of both age and verbal fluency group. (AA = Ambiguous Words, UW = Unambiguous Words)
Figure 7. Rereading times on the target region in the syntactic prose contexts only, as a function of both age and verbal fluency group.
References


