The Effects of Age-of-Acquisition on Ambiguity Resolution: Evidence from Eye Movements

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Words that are rated as acquired earlier in life receive shorter fixation durations than later acquired words, even when word frequency is adequately controlled (Juhasz & Rayner, 2003; 2006). Some theories posit that age-of-acquisition (AoA) affects the semantic representation of words (e.g., Steyvers & Tenenbaum, 2005), while others suggest that AoA should have an influence at multiple levels in the mental lexicon (e.g. Ellis & Lambon Ralph, 2000). In past studies, early and late AoA words have differed from each other in orthography, phonology, and meaning, making it difficult to localize the influence of AoA. Two experiments are reported which examined the locus of AoA effects in reading. Both experiments used balanced ambiguous words which have two equally-frequent meanings acquired at different times (e.g. *pot, tick*). In Experiment 1, sentence context supporting either the early- or late-acquired meaning was presented prior to the ambiguous word; in Experiment 2, disambiguating context was presented after the ambiguous word. When prior context disambiguated the ambiguous word, meaning AoA influenced the processing of the target word. However, when disambiguating sentence context followed the ambiguous word, meaning frequency was the more important variable and no effect of meaning AoA was observed. These results, when combined with the past results of Juhasz and Rayner (2003; 2006) suggest that AoA influences access to multiple levels of representation in the mental lexicon. The results also have implications for theories of lexical ambiguity resolution, as they suggest that variables other than meaning frequency and context can influence resolution of noun-noun ambiguities.

Keywords: Reading, Eye movements, Word processing, Lexical ambiguity, Age-of-Acquisition

Introduction

Over the past three decades, a sizeable literature demonstrating that words acquired earlier in life are processed faster than words acquired later in life has been amassed (see Juhasz, 2005 for a review). These age-of-acquisition (AoA) effects have been observed in a number of experimental tasks, including word naming (e.g. Gerhand & Barry, 1998; Ghyselinck, Lewis, & Brysbaert, 2004; Morrison & Ellis, 1995), lexical decision (e.g. Cortese & Khanna, 2007; Ghyselinck et al., 2004; Menenti & Burani, 2007; Morrison & Ellis, 1995), picture naming (e.g. Catling & Johnston, 2006; 2009; Ellis & Morrison, 1998), and semantic categorization (e.g. Brysbaert, Van Wijnendaele, & De Deyne, 2000; Catling & Johnston, 2006; 2009; Menenti & Burani, 2007). AoA has also been found to influence fixation durations on words embedded in neutral sentences (Juhasz & Rayner, 2003; 2006).

While AoA effects are now widely accepted, the mechanism by which these effects are produced is still

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under debate. Some researchers have questioned whether AoA effects are really distinct from frequency effects (e.g. Zevin & Seidenberg, 2002; 2004), as most words learned early in life will be experienced more frequently over the lifespan, as compared to words learned later in life. However, AoA effects can be separated from those of word frequency, as they persist when adult word frequency, cumulative lifespan frequency, and rated familiarity are adequately controlled (e.g. Cortese & Khanna, 2007; Juhasz & Rayner, 2003; 2006). In addition, specific predictions for AoA made by the cumulative frequency hypothesis have not been supported by experimental data (Ghyselink et al., 2004; Menenti & Burani, 2007).

Some theories of AoA attempt to localize the influence of AoA in the mental lexicon to one level of representation, or suggest that AoA represents a general learning property which should affect access to all levels of representation. The phonological completeness hypothesis is an example of the former, arguing that the age at which a word is acquired affects the nature of that word's phonological representation. According to this hypothesis, early-acquired words have more complete, holistic phonological representations than do late-acquired words (e.g., Brown & Watson, 1987; Gerhand & Barry, 1998). Recent experiments have largely not supported this conceptualization (e.g., Monaghan & Ellis, 2002). According to the semantic locus hypothesis, early-acquired words are processed faster due to a difference in semantic representations for these words (see Brysbaert et al., 2000). The semantic locus hypothesis gained support from the modeling effort of Steyvers and Tenenbaum (2005), which demonstrated that words entered into a semantic system early in training become "semantic hubs" with many connections to other concepts. Since lexical search is biased towards more highly connected concepts, the meaning of early-acquired words should thus be processed faster than later-acquired concepts (see Gullick & Juhasz, 2008 for support for this theory using a cued-recall paradigm).

In contrast, the network plasticity hypothesis is a theory of AoA effects which suggests that AoA is a general learning phenomenon (Ellis & Lambon Ralph, 2000). This theory was developed based on simulations using a connectionist model where patterns entered early in training were encoded better than patterns entered into the system later due to a decrease in system plasticity over time. In terms of word recognition, this would suggest that early-learned words are better encoded in the mental lexicon due to greater plasticity at the time they are learned. Importantly, this theory views AoA effects as occurring at all levels of representation, including access to orthography, phonology, and semantics.

Brysbaert and Ghyselinck (2006) have suggested that AoA effects may actually be a composed of both a frequency-related component and a frequency-independent component. The frequency- related component is observed in tasks such as word naming and lexical decision, where effect sizes for AoA and word frequency are often very similar. Both therefore may indicate a general learning phenomenon. In comparison, tasks such as picture naming yield an AoA effect an order of magnitude larger than word frequency effects.

Attempts to distinguish these various theories of AoA effects have often examined the relative contribution of AoA to experimental tasks thought to tap into different levels of representation in the mental lexicon (e.g., Catling & Johnston, 2006; 2009; Ghyselink et al., 2004; Menenti & Burani, 2007). Recording eye movements while readers recognize printed words also provides a valuable opportunity to examine how AoA may impact the organization of the mental lexicon. In order to read and understand a word in text, access to its orthography, phonology, and meaning must occur. Tasks such as word naming and lexical decision only allow for the investigation of words one at a time, and are therefore a less-natural reading task. Recording eye movements during reading allows one to study reading with little disruption (see Rayner, 1998 for a discussion of eye movements in reading). As such, one can examine how AoA affects word recognition during reading in context.

As mentioned above, Juhasz and Rayner (2003; 2006) observed effects of AoA on fixation durations in neutral sentences. One difficulty with drawing strong conclusions from Juhasz & Rayner (2003; 2006) regarding the locus of AoA effects is that different lexical items were used in the early and late AoA conditions. Because of this design, the orthography, phonology, and meaning of the early- and late- acquired words differed. Thus, the resultant AoA effects on eye fixation durations could be attributable to access to the word's orthographic representation, phonological representation, semantic representation, or to all three. This criticism obviously applies to all past studies of AoA effects using word stimuli. One way to combat this problem and provide evidence as to whether AoA influences access to semantic representations of words during reading, is to use ambiguous words with more than one meaning. Such stimuli would allow one to control the orthography and phonology of word, and to examine whether AoA influences access to the meaning of the ambiguous word.

Many eye movement studies have examined how ambiguous words are processed in context (see Duffy, Kambe, & Rayner, 2001 for a review). These studies all

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support the finding that the frequency of the meanings of an ambiguous word has a strong influence on the processing of that word. In the eye movement literature, two types of ambiguous words have been examined. Biased ambiguous words have one dominant (i.e., highly-frequent) meaning and one subordinate (low-frequency) meaning. Balanced ambiguous words have two meanings with very similar frequencies. A clear pattern emerges when both meanings of the ambiguous word are nouns (see Frazier & Rayner, 1987 and Pickering & Frisson, 2001 for eye movement studies with noun-verb and verb-verb ambiguities): when the context disambiguating the meaning of the ambiguous noun follows the word (and thus the context before is neutral), processing time on the balanced words is greater than a control word matched for length, frequency, and contextual fit (e.g., Duffy, Morris, & Rayner, 1988; Rayner & Duffy, 1986; Rayner & Frazier, 1989). However, biased ambiguous words are processed similarly to their matched control word when the prior context is neutral (e.g. Duffy et al., 1988). When the post-target context indicates the subordinate meaning of the biased ambiguous word, fixation times are longer on the disambiguating region when compared to a balanced ambiguous word. In addition, fixation times on the disambiguating region of ambiguous words in general are longer than for control words (Rayner & Duffy, 1986, Rayner & Frazier, 1989).

Past research has reliably shown that when disambiguating context precedes the ambiguous target word, processing times for balanced and biased words do not differ from their matched controls as long as the context disambiguates the dominant meaning of the biased word (Duffy et al., 1988; Rayner & Frazier, 1989; Binder & Morris, 1995). If the prior context disambiguates the subordinate meaning of a biased ambiguous word, processing time is elevated. The increased processing time is called the *subordinate bias effect* (e.g., Binder, 2003; Binder & Rayner, 1998; Rayner, Cook, Juhasz, & Frazier, 2006; Sereno, O'Donnell, & Rayner, 2006). An ongoing debate in the study of the characteristics of ambiguous words centers on developing a model explaining how they are processed and organized in the mental lexicon. According to interactive accounts of the mental lexicon, sentence context should be able to select for the correct meaning of the ambiguous word (e.g., McClelland, 1987), while exhaustive access models assume that all meanings of the word are always accessed, regardless of context (e.g., Duffy et al., 1988; Rayner & Frazier, 1989). The reordered access model is the most supported in the current literature (Dopkins, Morris, & Rayner, 1992; Duffy et al., 1988; Sereno, 2005; Sereno et al., 2006; Sheridan, Reingold, & Daneman, 2009), and proposes context to raise the level of activation of the supported meaning without influencing the inappropriate meaning (Duffy et al., 1988). Selection of a word meaning may thus depend on both its frequency and the sentence context.

The purpose of the present experiments was to investigate whether semantic AoA effects could be observed independently of differences in word frequency, orthography, and phonology between early- and late-acquired items. To accomplish this, balanced ambiguous words were selected, thereby providing identical orthographies and phonologies and well-matched frequencies across meaning. If an AoA effect is observed through eye movements on these items, it would lend strong support to theories which suggest that AoA can influence access to semantic representations for words. Often, reading times for an ambiguous word are compared to a control word matched in frequency. The appropriate frequency to match on, however, has been debated (see Sereno et al., 2006). We chose to circumvent this issue by adopting the same method as Rayner et al. (2006) and Sheridan et al. (2009). We thus examined the reading times on an ambiguous word when one meaning was supported by the context, and compared it to the same ambiguous word when the context supported the other meaning. The results of this study will inform models and theories of AoA effects in the mental lexicon as well as provide information on an additional variable (AoA) which may influence lexical ambiguity resolution in context.

Experiment 1

Method

Participants. A total of 50 Wesleyan University students participated in the eye-tracking experiment. They received either course credit or were paid seven dollars. All participants were native speakers of English and had normal or corrected-to-normal vision.

Apparatus. Eye movements were recorded via an Eyelink 1000 eye tracker (SR Research Ltd). This eye-tracker samples eye position every millisecond and is interfaced with two computers. Participants were seated 83 cm away from a ViewSonic CRT monitor where the sentences were displayed. Sentences were presented in 14 pt. Courier New font in lower case (except where upper case was appropriate). At this viewing distance, approximately 3.62 characters subtend one degree of visual angle. Participants viewed the sentences binocularly, although eye position was only recorded from the right eye. Head movements were reduced to the extent possible via a chin rest and head rest. Stimuli

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display was controlled by the EyeTrack software package (http://www.psych.umass.edu/eyelab/software/).

Stimuli. Balanced ambiguous words were selected from previously published sources (Cramer, 1970; Geis & Winograd, 1974; Gorfein, Viviani, & Leddo, 1982; Nelson, McEvoy, Walling, & Wheeler, 1980; Perfetti, Lindsey, & Garson, 1971), from ratings previously collected at the University of Massachusetts, Amherst (UMass) (Duffy et al., 1988; Sereno & Pacht, 1992), and from new ratings collected at UMass for this project. When meaning frequencies for a word appeared in more than one source, the frequencies were averaged. In the new ratings, 25 UMass undergraduates were provided with 80 words and were asked to write down the first associated word which came to their mind. The 80 words consisted of 59 ambiguous words and 21 non-ambiguous filler words. Twenty-eight ambiguous words deemed to have two equally-frequent meanings were selected for an age-of-acquisition rating. In these ratings, each of the 28 words was provided with a short definition of the meaning (e.g., Tick: a small parasitic animal). Participants were asked to rate the age at which they acquired that particular *meaning* of the ambiguous word on a 1-7 scale (see Gilhooly & Logie, 1980), where a rating of 1 indicates that the word was learned between 0-2 years of age, and a rating of 7 indicates that the word was learned at age 13 or older. Two questionnaires were created so that each participant would only rate one meaning for each ambiguous word. Twenty UMass undergraduates completed this meaning AoA rating. From these ratings, 16 balanced ambiguous words were selected where one meaning was rated as being acquired earlier than the other meaning. The stimuli are presented in the Appendix. Stimuli characteristics are displayed in Table 1.

Table 1.
Stimuli Characteristics.

Measure	*Early AoA Meaning*	*Late AoA Meaning*
Word length	4.56 (0.96)	4.56 (0.96)
Word Frequency	42.5 (57.3)	42.5 (57.3)
Meaning Frequency (%)	46.7 (11.7)	44.1 (10.3)
Meaning AoA	2.82 (1.05)	5.15 (0.88)

Note: Numbers in parentheses are standard deviations. Word frequencies were measured per million from the Educator's Word Frequency Guide (Zeno, Ivens, Millard, & Duvvuri, 1995). Meaning frequencies did not differ significantly (p>.50). Meaning AoA was rated on a 1-7 scale and differed significantly as a function of condition (t(15) = 7.56, p<.001).

Two sentences were created for each balanced ambiguous word. In one sentence, the beginning context provided support for the early-acquired meaning; in the second, the beginning context supported the late-acquired meaning. Both sentences had an identical post-target word. Sentences were rated for how well each target word fit into the sentence on a 1-7 scale (with higher numbers indicating a better fit). Twenty Wesleyan University undergraduates rated the sentences. Two rating surveys were created so that each participant only rated one sentence frame for each target word. The ratings did not differ as a function of whether the early- or late-acquired meaning was implied by the sentence context ($p>.1$). Example sentences are displayed in Table 2. Each sentence was less than 80 characters long and occupied a single line of the computer screen from which it was read.

Table 2.
Example Sentence Frames used in Experiment 1.

EARLY-ACQUIRED MEANING:
Sarah hates washing out the largest **pot** and doesn't use it often.
You shouldn't drink with a **straw** after having your wisdom teeth removed.
Jean could still hear the quiet **tick** from the clock in the other room.
LATE-ACQUIRED MEANING:
My friend spends all of his money on **pot** and doesn't pay his bills.
The farmer loaded his truck with grain and **straw** after having cut it down.
Tim knew he had been bitten by a **tick** from the bullseye on his back.

Procedure. Upon arrival, participants were given an informed consent form to read and sign. Next, they were given verbal instructions explaining the procedure. A three-point single-line calibration was conducted. Participants were asked to look at a black box on the left side of the computer screen to trigger the sentence to appear on the screen. If at any point the sentence did not appear, participants were recalibrated. Participants were asked to read the sentences for comprehension, at their own rate. To move onto the next trial, they were instructed to press a button on a controller. In addition to

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the 16 experimental sentences, participants read 44 filler sentences. The first 5 sentences were for practice only and appeared in a specified order. After this point, the experimental and filler sentences were randomized by the experimental software. After 25% of the sentences, participants were provided with comprehension questions requiring a yes or no answer on their controller.

Design and Data Analysis. Trials for which there were track losses on the pre-target, target, or post-target region were not included in the analysis, leading to the removal of approximately 4.01% of the data. Fixations shorter than 80 ms and on adjacent characters were combined. Additional fixations shorter than 100 ms or longer than 1000 ms were removed by the data analysis software.

The following dependent measures were analyzed on the target word: *First fixation duration*, the duration of the first fixation on the target word irrespective of the number of fixations the word receives; *Gaze duration*, the sum of all first-pass fixations on the target word prior to the eyes moving off of the target word; *Percentage of regressions* into and out of the target word; *Go-past duration*, the time spent reading the target word prior to the eyes moving to the right of the target plus any regressions back to the previous context; *Total fixation duration*, the sum of all fixations on the target word including re-reading. In addition, gaze duration and go-past duration on the post-target word were analyzed as was the percentage of regressions out of the post-target word. Paired-sample t-tests were used to analyze dependent measures on the ambiguous word in the early-acquired meaning condition and the late-acquired meaning condition. Analyses were computed by participants (t_1) and by items (t_2). Meaning AoA was considered both a within-participant and within-item variable.

Results

Outliers which were 2.5 standard deviations above the condition means for each duration measure were removed prior to analysis. This led to the removal of between 2.58% - 3.72% of the fixation durations, depending on the measure. Trials in which the target or post-target word was not fixated did not contribute to the computation of data deletion.

Participant means are displayed in Table 3. A significant processing advantage was apparent when the sentence context supported the early-acquired meaning of the balanced ambiguous word. First fixation durations were 11 ms shorter for early AoA meanings ($t_1(49) = 2.62$, $p<.025$; $t_2(15) = 2.05$, $p=.058$). This effect grew to 15 ms in gaze durations ($t_1(49) = 2.38$, $p<.025$; $t_2(15) = 2.28$, $p<.05$) and 24 ms in total fixation duration ($t_1(49) = 3.26$, $p<.01$; $t_2(15) = 3.42$, $p<.01$). Go-past duration on the target word was not significantly influenced by meaning AoA (both ps>.1). There were significantly more regressions into the target word when the late AoA meaning was supported by the sentence context ($t_1(49) = 4.07$, $p<.001$; $t_2(15) = 2.66$, $p<.025$). Regressions out of the target word were not influenced by meaning AoA (both ps>.25).

Table 3.
Participant means for Experiment 1.

Measure	*Early AoA Meaning*	*Late AoA Meaning*
Target Word:		
First fixation (ms)	218 (31)	229 (30)
Gaze Duration (ms)	232 (38)	247 (35)
Go-Past Duration (ms)	267 (58)	284 (71)
Total Fixation Duration (ms)	250 (51)	274 (51)
Regressions out of (%)	9.5 (12.7)	8.3 (11.6)
Regressions into (%)	5.1 (8.8)	12.7 (15.6)
Post-Target Word:		
Gaze Duration (ms)	274 (67)	285 (56)
Go-Past Duration (ms)	302 (75)	348 (71)
Regressions out of (%)	4.9 (9.1)	11.4 (12.7)

Note: Numbers in parentheses represent standard deviations.

Meaning AoA also influenced processing of the post-target word, as indicated by significantly longer go-past times on the post-target ($t_1(49) = 3.71$, $p<.01$; $t_2(15) = 3.53$, $p<.01$) and a greater percentage of regressions out of the post-target in late meaning AoA sentences ($t_1(49) = 3.33$, $p<.01$; $t_2(15) = 2.24$, $p<.05$). Gaze durations on the post-target word did not differ significantly as a function of condition (ps>.1).

Supplementary Analyses. Sentence contexts were created which strongly biased either the early- or late-acquired meaning of the balanced ambiguous word. As stated above, the words were rated as fitting equally well into each sentence frame. However, it is possible that the sentence contexts for one meaning of the ambiguous word

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resulted in a higher predictability of the target word, as compared to the other. In order to assess the degree of predictability for these ambiguous words, a cloze task was conducted where participants were presented with the beginning sentence context and were asked to provide one word that could fit as the next word in the sentence. Sixteen Wesleyan University undergraduates participated in the rating experiment. Two cloze rating surveys were created so that each participant only rated one sentence frame for each ambiguous word. The average cloze rating for the early meaning AoA items was 17.97%, compared to 3.13% for the late meaning AoA items. This difference was statistically significant ($t_2(15) = 2.41$, $p<.05$). To confirm that the eye-tracking results were in fact due to AoA of meaning, instead of predictability, the four items which showed the largest advantage in predictability for early, as compared to late AoA, words were removed. This deletion reduced the cloze ratings for the early and late meaning AoA items to 8.33% and 4.17%, respectively, which was not significantly different ($p>.35$). Items analyses for each measure were repeated with the smaller set of items. While this did reduce the power of the analyses (due to the small set of 12 items), there were still statistically significant effects of meaning AoA on first fixation duration on the target word ($t_2(11) =2.33$, $p<.05$); total fixation duration on the target word ($t_2(11) = 2.72$, $p<.05$), and the go-past duration on the post-target word ($t_2(11) = 3.51$, $p<.01$). The effect of meaning AoA of the target word on gaze duration was marginally significant with the reduced number of items ($t_2(11) = 2.05$, $p=.065$), while the effects on regressions into the target word and out of the post-target word did not reach significance in this analysis (both $ps>.1$)[1].

Discussion

Clear effects of meaning AoA for balanced ambiguous words are demonstrated in this experiment. Early processing measures such as first fixation duration are shorter for balanced ambiguous words when sentence context provides support for an early-acquired meaning, as compared to a late-acquired meaning. These effects persist into later processing measures, like total fixation duration, which take regressions back into the target word into account, as well as go-past duration on the post-target word. This continuing influence on the post-target word (identical in the two sentence frames) suggests that context which comes immediately after the ambiguous word is easier to integrate into the sentence when the meaning of the ambiguous word is earlier-acquired. Post-hoc tests on a restricted set of items indicated that the processing differences observed between early and late meaning AoA are not simply due to a difference in predictability between the two sentence contexts (see also Footnote 1).

In the present experiment, orthography, phonology, word-form frequency, and meaning frequency were controlled between the two meaning AoA conditions. The results must therefore indicate that AoA influences access to the semantic representations for the ambiguous words. This finding argues against the theory that AoA is a purely phonological variable, since phonology was here controlled. In addition, the results provide further evidence against AoA acting merely as a word frequency effect, as two types of frequency (word-form and meaning frequency) were controlled. The data do support theories of AoA suggesting that AoA can influence access to semantic representations. According to the semantic locus hypothesis of AoA effects, early-acquired words have more richly connected semantic representations than later-acquired words, demonstrated by Steyvers and Tanenbaum (2005). These effects could also be incorporated into the network plasticity hypothesis of Ellis and Lambon Ralph (2000). Under this hypothesis, AoA should exert an influence on access to semantic representations of a word, and should also influence access to orthographic and phonological representations, at least to some extent.

The results suggest that while the items used in the experiment are balanced in terms of meaning frequency, they act as biased due to the difference in AoA between the two meanings. Thus, the late-acquired meaning acts as a subordinate meaning, and context disambiguating for the late-acquired meaning produces a subordinate bias effect. As discussed earlier, the location of the disambiguating context has a strong influence on eye movement behavior when readers encounter ambiguous words (e.g. Duffy et al., 1988). The present experiment suggests that frequency is not the only factor that influences ambiguity resolution. A second experiment was conducted using these early- and late-acquired meaning items where sentence context prior to the ambiguous word was neutral, and the disambiguating context was placed after the ambiguous word. Based on the hypothesis that meaning AoA causes these items to act as biased ambiguous words, we expected that late processing measures which take regressions back to the ambiguous word into account would show sensitivity to meaning AoA.

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Experiment 2

Method

Participants. A total of 55 students at Wesleyan University participated in the eye-tracking experiment. All participants were native English speakers and had normal or corrected vision. They were paid seven dollars for their time or received course credit.

Apparatus. The apparatus was identical to Experiment 1.

Stimuli. The sixteen balanced ambiguous words from Experiment 1 were used in this study. Two sentence frames were constructed for each word. In both frames, the disambiguating information appeared after the target word, and the sentences were identical up through the post-target word for each ambiguous word. In one sentence frame, the disambiguating information biased the early-acquired meaning of the word, and in the other the disambiguating information biased the late-acquired meaning. Example sentences are displayed in Table 4. Each participant only read one sentence frame for each balanced ambiguous word. Each sentence was less than 80 characters and occupied a single line on the computer screen.

Table 4.
Example Sentence Frames used in Experiment 2.

EARLY-ACQUIRED MEANING:
Michelle's favorite type of **rock** is definitely pink quartz, not amethyst.
Jasper noticed that the **yard** of the office building has weeds everywhere.
Lynn found the **pitcher** to be a great athlete who was a credit to his team.
LATE-ACQUIRED MEANING:
Michelle's favorite type of **rock** is definitely heavy metal, not alternative.
Jasper noticed that the **yard** of fabric looked like it was a few inches short.
Lynn found the **pitcher** to be too heavy to carry when filled with water.

Predictability of the ambiguous words was assessed via a cloze norm where participants were provided with the beginning sentence context and were asked to write one word which could fit as the next word in the sentence. Sentences were split into two questionnaires, and 8 Wesleyan University undergraduates rated each sentence frame. None of the ambiguous words were provided as a possible completion for any sentence frame. In addition, 20 Wesleyan University undergraduates rated each sentence on a 1 to 7 scale in terms of how well the ambiguous word fit into the sentence frame. The average ratings did not differ as a function of meaning AoA (p>.1).

Procedure. The procedure was identical to that for Experiment 1 with the following exceptions: In addition to the 16 experimental sentences, participants read 104 filler sentences. Approximately 23% of the trials were comprehension questions which required a yes or no answer on their controller.

Design and Data Analysis. Track losses were removed from the data in the same manner as in Experiment 1, with the addition that trials were also removed if there was a track loss in the disambiguating region. This led to the removal of approximately 9.6% of the trials. The disambiguating region was defined based on experimenter intuitions and consisted of 1-5 words which provided information about the intended meaning of the ambiguous word. Fixation duration cut-offs were identical to Experiment 1. The same dependent measures were analyzed with the addition of the percentage of regressions out of the disambiguating region.

Results

Outliers were removed from the duration measures in the same manner as in Experiment 1, leading the removal of between 1.8% - 4.4% of the data, depending on the dependent measure. Participant means are displayed in Table 5. There were no statistically significant differences in processing the ambiguous word when the early and late AoA meanings were supported by context following the target word in first fixation durations (ps>.10), go-past duration (ps>.25), total fixation duration (ps>.50), regressions out of the target word (ps>.40), or regressions into the target word (ps>.50). The only effect that approached significance was a 9 ms advantage in gaze durations for ambiguous words with a late-acquired meaning ($t_1(54) = 1.74$, p=.087; $t_2(15) = 2.40$, p<.05). This effect is likely spurious, since the sentence context was identical through the post-target word. In addition,

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there were no significant differences observed on the post-target word in terms of gaze duration, go-past duration, or percentage of regressions out (*p*s>.10). Finally, the rate of regressions out of the disambiguating region was nearly identical for the early-AoA meaning sentences (16.33%) compared to the late-AoA meaning sentences (16.50%) and were not statistically different (*p*s>.7).

Table 5.
Participant means for Experiment 2.

Measure	*Early AoA Meaning*	*Late AoA Meaning*
Target Word:		
First fixation (ms)	224 (34)	216 (33)
Gaze Duration (ms)	232 (34)	223 (35)
Go-Past Duration (ms)	269 (67)	257 (57)
Total Fixation Duration (ms)	282 (63)	277 (69)
Regressions out of (%)	9.6 (16.6)	7.7 (10.5)
Regressions into (%)	13.7 (13.6)	15.0 (15.1)
Post-Target Word:		
Gaze Duration (ms)	241 (45)	239 (40)
Go-Past Duration (ms)	278 (72)	262 (57)
Regressions out of (%)	7.0 (9.6)	6.0 (11.0)
Disambiguating Region:		
Regressions out of (%)	16.3 (18.0)	16.5 (16.4)

Note: Numbers in parentheses represent standard deviations.

Supplementary Analyses.

In order to further examine the processing of context after the balanced ambiguous word, a region was created consisting of the sentence context occurring after the post-target word. Three measures were examined for this region: gaze duration, go-past duration and regressions out of the region. Since these regions differed in length for the two meanings of each ambiguous word, gaze duration and go-past duration were converted to a millisecond per character measure. Confirming the initial analyses, processing time on the context was nearly identical for the early- and late-acquired sentences for gaze duration (30.76 ms/char for early acquired, 30.74 for late-acquired) and go-past time (42.14 for early-acquired, 42.95 for late-acquired). Regressions out of these regions was also nearly identical (28.2% for early-acquired, 27.6% for late-acquired). None of the differences reached significance (all *p*s>.5).

Discussion

The pattern of eye movement data did not support our predictions that meaning AoA caused these balanced ambiguous words to behave like biased ambiguous words. Instead, the eye movement data is what would be expected for balanced ambiguous words: encountering a context after the ambiguous word which disambiguates the late-acquired meaning does not result in a greater percentage of regressions from the disambiguating region or back to the ambiguous word. There is also no difference in total fixation durations on the ambiguous word and no difference in processing later context associated with the two meanings.

To better understand how the location of sentence context influenced the processing of these ambiguous words, an additional late processing measure was analyzed. Second-pass time represents the re-reading time on the target word. The data from the two experiments was combined into a 2 x 2 ANOVA, with the first factor being the location of the disambiguating context (prior to the ambiguous word or after the ambiguous word) and the second factor being the meaning AoA. The context location variable was treated as a between-subjects and a within-items variable in the analysis. When disambiguating context preceded the ambiguous word, second-pass times were shorter for early-acquired meanings (16.6 ms) compared to late-acquired meanings (39.4 ms). However, when the disambiguating context followed the ambiguous word, the second-pass times were nearly identical for early-acquired (57.2 ms) and late-acquired (56.8 ms) meanings. Second-pass times were significantly longer in the context-following condition ($F_1(1,103) = 13.57$, $MSe = 3248$, $p<.001$; $F_2(1,15) = 5.60$, $MSe = 2238$, $p<.05$). The main effect of meaning AoA and the interaction between AoA and context location did not reach significance in the items analysis (main effect: $F_1(1,103) = 4.76$, $MSe = 1375$, $p<.05$; $F_2(1,15) = 1.86$, $MSe = 1220$, $p>.15$; interaction: $F_1(1,103) = 5.14$, $MSe = 1375$, $p<.05$; $F_2(1,15) = 2.39$, $MSe = 702$, $p>.1$). The results from this additional analysis do suggest that the location of context impacts the processing of these ambiguous words. Disambiguating context following the ambiguous word results in significantly longer rereadings of the ambiguous word than when context precedes the

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ambiguous word. However, the amount of rereading is not sensitive to the meaning AoA of the ambiguous word when the disambiguating context follows the ambiguous word.

General Discussion

The results of Experiment 1 demonstrate that meaning AoA can influence processing of ambiguous words when the preceding context supports the early-acquired meaning of the ambiguous word. This effect occurs immediately, as it is observed even in the first fixation duration on the ambiguous word. The effect of meaning AoA also persists into later processing measures. However, when the disambiguating context follows the ambiguous word (as was the case in Experiment 2), the effect of meaning AoA is eliminated. In this case, meaning frequency appears to be the more influential variable, and the eye movement behavior seems to indicate that readers are selecting each alternative meaning of the ambiguous word roughly equally. These results may inform theories of AoA and the implications of AoA's influence on ambiguity resolution during reading.

The findings from Experiment 1 provide more support for the idea that AoA effects are separate and dissociable from word frequency effects. Specifically, word-form frequency and meaning frequency were matched in the early and late AoA conditions in the present experiment, yet AoA still had a significant effect on processing the ambiguous words in Experiment 1. In Experiment 2, when sentence context followed the ambiguous word, the fixation durations for late processing measures behaved as would be expected for balanced ambiguous words with two equally-frequent meanings. Although there was no effect of meaning AoA in Experiment 2, this finding still strengthens the case that AoA and word frequency are separate effects by validating that the results of Experiment 1 could not be merely due to faulty matching of the stimuli on meaning frequency. The results of Experiment 1 also suggest that AoA effects on eye fixation durations are not solely due to access to the phonological representations of words, providing more evidence against the phonological completeness hypothesis.

The meaning AoA effect observed in Experiment 1 suggests that AoA can impact access to semantic representations during reading. However, this effect is context dependent, as it is eliminated when disambiguating context follows the ambiguous words. The lack of a meaning AoA effect in neutral context stands in contrast to the effects of AoA reported by Juhasz and Rayner (2003; 2006) on fixation durations in neutral sentence contexts. The pattern of results across these experiments thus suggests that semantic access can be influenced by the age at which a particular word meaning is acquired, but is not the sole locus of AoA effects in word recognition.

Both the semantic locus hypothesis (as modeled by Steyvers & Tenenbaum, 2005) and the network plasticity hypothesis (Ellis & Lambon Ralph, 2000) would suggest that early-acquired meanings of balanced ambiguous words are more likely to be accessed in neutral contexts. The present experiments suggest that this does not happen, and that effects of meaning AoA are only apparent when supportive context is provided prior to the word. These results are damaging to a strong version of the semantic locus hypothesis. However, it may be possible for them to be incorporated into the network plasticity hypothesis, as this theory allows AoA to influence access to all levels of representation in the mental lexicon. Additional simulations with the network plasticity model would need to be conducted to examine whether it can incorporate the present findings.

The present pattern of results is also informative for theories of lexical ambiguity resolution. The majority of theories have focused exclusively on the frequency of meanings in ambiguous word and how (or if) context interacts with meaning frequency (e.g., Duffy et al., 1988; Rayner & Frazier, 1989). These theories are based on quite clear experimental findings showing differing results for balanced and biased ambiguous nouns as a function of the location of supporting contextual information. The current study provides a caveat to these experimental findings by suggesting that some ambiguous words can act as biased ambiguous words when the disambiguating context precedes the ambiguous word, and act as balanced ambiguous words when the disambiguating context follows the ambiguous word. It is difficult to see how current theories of lexical ambiguity resolution would incorporate these "hybrid" ambiguous words. On the other hand, the results also confirm the importance of meaning frequency in lexical ambiguity resolution. Since AoA is highly correlated with word frequency, it is reasonable to assume that many of the biased ambiguous words used in previous ambiguity studies have had meanings differing both in their frequency of occurrence and the age at which the two meanings were acquired. The present experiments suggest that the influence of meaning AoA is dissociable from the influence of meaning frequency, and that meaning frequency is the more important variable for influencing eye fixation behavior when context preceding the ambiguous word is neutral.

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At a more general level, these results suggest that additional factors related to the meanings of ambiguous words may impact lexical ambiguity resolution. As earlier stated, one factor that has previously been found to impact lexical ambiguity processing is the syntactic category of the meaning. Resolution of both noun-verb ambiguities (Frazier & Rayner, 1987) and verb-verb ambiguities (Pickering & Frisson, 2001) has been found to be delayed relative to the more typically studied noun-noun ambiguities. The current study suggests that even for noun-noun ambiguities, there are properties of the two meanings other than meaning frequency which may influence lexical ambiguity resolution. While the current experiments focused on the age at which a particular meaning is acquired, one can imagine that other aspects of the meaning of ambiguous words may also be relevant, such as the imageability or concreteness of the meaning. Juhasz and Rayner (2003) demonstrated that word concreteness had an effect on gaze durations on target words over and above effects attributable to the word's length, frequency, AoA, and familiarity. The relative concreteness of the two meanings of an ambiguous word may likewise influence the processing over and above effects of meaning frequency and meaning AoA. Frazier and Rayner (1990) did consider the role of meaning concreteness in lexical ambiguity resolution, finding meaning frequency to be the main variable influence fixation durations. However, they also employed a mixture of balanced and biased ambiguous words; this increased variability may have resulted in keeping even the effect of meaning frequency from reaching significance. Thus a stronger manipulation of meaning concreteness, when meaning frequency is systematically controlled, may yield different results.

In conclusion, the present study demonstrates that AoA can influence access to semantic representations for ambiguous words when the meaning is disambiguated prior to fixation. Meaning frequency is the more influential variable when the sentence context is neutral prior to the ambiguous word. These results support theories of AoA effects that allow a role in access to semantic representations, while also suggesting that the semantic locus is not completely sufficient to explain AoA effects in word recognitions. In addition, the current results suggest that resolution of noun-noun ambiguities can be influenced by variables other than meaning frequency, a factor which theories and models of lexical ambiguity resolution must take into consideration.

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Appendix

Each balanced ambiguous word used in the Experiments is provided along with the definition for the Early Acquired meaning (EA) and Late Acquired meaning (LA) given to participants during the meaning AoA rating.

BUCK	A dollar (EA)
	A male deer (LA)
CAPE	A sleeveless piece of clothing (EA)
	A point of land that projects into water – e.g. Cape Cod (LA)
CASE	A container to hold something (EA)
	An example or situation (LA)
CRANE	A machine for lifting heavy objects (EA)
	A type of bird (LA)
DEED	An act or something performed (EA)
	A legal document (LA)
MASS	A church service (EA)
	A large amount (LA)
PANEL	A flat piece of wood (EA)
	A group of people participating in a discussion (LA)
PITCHER	A person in baseball who throws the ball to the batter (EA)
	A container for holding liquids (LA)
POT	A rounded container used in cooking (EA)
	Marijuana (LA)
PUNCH	A blow with the fists (EA)
	A beverage of fruit juices (LA)
QUACK	The sounds a duck makes (EA)
	A charlatan or fraud (LA)
ROCK	A stone (EA)
	A type of music (LA)
STRAW	A plastic tube used for drinking (EA)
	Stalks of grain after being cut (LA)

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TICK	The sound a clock makes (EA)
	A small parasitic animal (LA)
VOLUME	The loudness of a sound (EA)
	A quantity or amount of liquid (LA)
YARD	An area of land next to a home (EA)
	A distance equal to three feet (LA)

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Footnotes

1. In order to validate these results, linear mixed effects models were conducted using duration measures as the dependent variables. These analyses were conducted in SPSS (IBM, Chicago, IL USA) using the MIXED program. Condition (Early vs Late meaning AoA) and percentage of cloze completions from each item were treated as fixed effects. Item and participant were considered random effects (see Brysbaert, 2007 for information on this procedure). When all items were included, and the effect of cloze performance was statistically accounted for, AoA condition was a marginally significant predictor of first fixation on the target (p=.065) and gaze duration on the target (p=.063). AoA condition was a significant predictor of total fixation duration on the target word (p < .01), go-past duration on the post-target word (p<.001) and gaze duration on the post target word (p<.05). As in the original analyses, go-past duration on the target word was not significantly predicted by condition (p>.35).

One item, *cape*, had a much higher cloze percentage for the early acquired meaning (75%) sentence compared to all other items. The difference between cloze performance between the early and late acquired meanings for this item was more than 2.5 standard deviations above the mean for all items, indicating it was an outlier. When this item was removed from linear mixed effects models, meaning AoA condition was now significant in first fixation on the target (p<.05) and gaze duration on the target (p<.025) in addition to the measures which were significant in the analyses with all items.

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