Cognitive Science 30 (2006) 311–345

Aging and the Use of Context in Ambiguity Resolution: Complex Changes From Simple Slowing

Karen Stevens Dagerman[a], Maryellen C. MacDonald[b], Michael W. Harm[c]

[a]*Department of Psychiatry and the Behavioral Sciences, University of Southern California*
[b]*Department of Psychology, University of Wisconsin-Madison*
[c]*Information Resources and Technology, Stanford University*

Received 4 June 2004; received in revised form 7 June 2005; accepted 11 June 2005

Abstract

Older and younger adults' abilities to use context information rapidly during ambiguity resolution were investigated. In Experiments 1 and 2, younger and older adults heard ambiguous words (e.g., *fires*) in sentences where the preceding context supported either the less frequent or more frequent meaning of the word. Both age groups showed good context use in offline tasks, but only young adults demonstrated rapid use of context in cross-modal naming. A 3rd experiment demonstrated that younger and older adults had similar knowledge about the contexts used in Experiments 1 and 2. The experiment results were simulated in 2 computational models in which different patterns of context use were shown to emerge from varying a single speed parameter. These results suggest that age-related changes in processing efficiency can modulate context use during language comprehension.

Keywords: Language comprehension; Cognitive aging; Ambiguity resolution; Computational modeling

1. Introduction

Language comprehension requires the integration of information over multiple levels of representation, including acoustic, orthographic, phonological, lexical, syntactic, and discourse levels. Much recent work suggests that developing representations at these linguistic levels, and interactions between these levels, can be characterized as a constraint-satisfaction process, in which information at each level shapes the developing representation in an interactive process (Kawamoto, 1993; MacDonald, Pearlmutter, & Seidenberg, 1994; Tanenhaus, Spivey-Knowlton, & Hanna, 2000). Precise timing of processing operations among the various levels of representation is crucial to take advantage of the constraints that exist at each level of representation. The necessity for rapid processing is especially notable with spoken language

Correspondence should be addressed to Maryellen C. MacDonald, Department of Psychology, 1202 West Johnson Street, University of Wisconsin-Madison, Madison, WI 53706–1696. E-mail: mcmacdonald@wisc.edu

comprehension, as the comprehender has relatively little control over the speed at which the input (the speech signal) arrives.

This characterization of language comprehension as a rapid constraint-satisfaction process has interesting implications for the study of language and aging, because the ability to process information rapidly appears to decline with age. This decline has been characterized in a variety of ways. One widely held view is that cognitive aging is associated with slowed perceptual, motor, and cognitive processes (e.g., Salthouse, 1996). An alternative is MacKay and Burke's (1990) transmission deficit hypothesis that information is passed through layers in a network less accurately in older than in younger people. Another alternative is that older adults are less able to inhibit activation of irrelevant information (Hasher & Zacks, 1988) or have other deficits in attentional modulation (Balota, Cortese & Wenke, 2001; Braver et al., 2001), and this attention-related deficit reduces efficiency in information processing. Others have characterized declining cognitive performance in aging as stemming from reductions in working-memory capacity (Just & Carpenter, 1992). Still others have pointed to perceptual declines as the primary source of poorer performance on cognitive tasks; on this view, memory, language comprehension, and other tasks suffer because the reduced visual or hearing acuity in older adults force them to process a degraded visual or acoustic stimulus (Schneider, Daneman, & Pichora-Fuller, 2002). These alternative perspectives invoke quite different mechanisms as the source of cognitive aging, but they have proved difficult to distinguish from one another, as they all seek to capture the basic idea that cognitive processes in older adults are somehow less efficient than in young people, and in many domains these accounts make highly similar predictions. Moreover, although it would be most parsimonious if a single factor underlay all changes in cognitive aging, in reality these accounts need not be mutually exclusive. For example, Kwong See and Ryan (1995) argued that declines in language comprehension in older adults stem from two factors: reduced speed and reduced ability to inhibit irrelevant information. Similarly, Van der Linden, Hupet, and Feyereisen (1999) argued that declines in verbal memory and language comprehension could be traced to three factors—declines in working-memory capacity, speed, and inhibition ability. They also suggested that these factors may interact in complex ways, such that the declines in working-memory capacity may be at least partially traceable to declines in speed and to inhibition deficits. Clearly substantial additional research will be required to further illuminate the source or sources of older adults' declines in performance on various cognitive tasks. Our immediate purpose here is to better understand the nature of these declines in specific language comprehension processes, and such an investigation can to some degree remain neutral about the ultimate source of these declines. Because we focus on the time course of language comprehension here, it is most straightforward to describe differences in young and old in terms of processing speed. Our use of this term is certainly consistent with accounts of slowing in cognitive aging (Salthouse, 1996) and with many characterizations of older adults as having slowed language processing abilities (e.g., Hale & Myerson, 1995; Myerson, Ferraro, Hale, & Lima, 1992; Stine & Hindman, 1994; Tun & Wingfield, 1999; Wingfield, Tun, Koh, & Rosen, 1999), but for now we leave open the possibility that speed changes could stem from or cause other changes, such as inhibitory ability. We return to these issues in the General Discussion.

Whatever the precise cause or causes of impaired information processing in older adults, the consequences of cognitive aging on language comprehension have been well documented. A number of studies show that older adults have more difficulty with language comprehension than do younger adults (for reviews, see Tun & Wingfield, 1997; Wingfield, 2000; Wingfield & Stine-Morrow, 2000). Researchers have documented age-related deficits in comprehension when speech is syntactically complex (Kemper, 1986, 1987; Kynette & Kemper, 1986), when speech is temporally compressed (Tun, Wingfield, Stine, & Mecsas, 1992), and when difficult inferential processing is required (Cohen, 1981; Zacks & Hasher, 1988; Zurif, Swinney, Prather, Wingfield, & Brownell, 1995). At points of particular difficulty, the processing demands of the task, in concert with slowed or otherwise inefficient language processing abilities, appear to result in less processing time for older adults, and subsequent comprehension is slowed or impaired.

2. Ambiguities and cognitive aging

A major locus of language processing difficulty is the presence of ambiguities in the input. Ambiguities exist at all levels of linguistic representation, from the earliest analysis of the speech signal to the highest level discourse representations. Comprehenders appear to cope with ambiguities in language through weighing probabilistic constraints from two major domains: the relative frequency of occurrence of alternative interpretations of the ambiguity in the language, and this context in which the ambiguity is embedded (e.g., MacDonald et al., 1994; Tanenhaus et al., 2000). These two kinds of information have a very different character. Frequency information, such as the fact that the prizefighter meaning of the ambiguous word *boxer* is more frequent in English than is the dog meaning, is widely held to emerge in the mapping between a word's phonological or orthographic code and its semantic codes, such that higher frequency interpretations of an ambiguous word will be activated more rapidly (Kawamoto, 1993; Seidenberg & McClelland, 1989). Thus the effects of frequency emerge as an intrinsic part of word recognition itself. By contrast, use of contextual information relies much more heavily on rapid computational processes that must be executed as more extensive language input is being processed. For example, comprehenders should interpret *boxer* differently depending on the prior context, so that the "fighter" meaning is promoted in the sentence *Because Freddy hung around the gym a lot, he knew that the boxer was unusually agitated,* and the "dog" meaning is promoted if *pet store* replaced *gym* in the sentence. Use of context in this case requires the comprehender to activate the meaning of *gym* or *pet store* and rapidly integrate this meaning with the alternative meanings of *boxer* so as to promote the contextually correct interpretation of the ambiguous word. The complexity of this computation is increased by the inevitable presence of ambiguity in the context itself, a point that is rarely noted in studies of context use. For example, *gym* is relatively unambiguous but has several related senses, some of which (e.g., a jungle gym, a school gym) are not associated with boxing. Indeed, it is not until the word *boxer* in this sentence that the child-related senses of *gym* are eliminated, so that the context of *boxer* is serving to disambiguate *gym* at the same time that *gym* is providing the context in which to interpret *boxer.* The context is even more ambiguous in the *pet store* version of the sentence, in that *pet* can be a noun (the correct sense here), a verb (to stroke an animal), or an adjective (meaning favorite), and *store* can be both a noun and a verb. Thus the extent to which *pet store* promotes the "dog" meaning of *boxer* is itself dependent on using frequency and other context information to resolve the ambiguities inherent in the context phrase. Several computational models have simulated the conjoined use of frequency and context use in lexical ambiguity resolution and have provided a mechanistic account of these processes (Cottrell, 1989; Kawamoto, 1993). A key feature of these models is the demonstration that context tends to have its major effect later during the ambiguity resolution process compared to frequency information, owing both to the relative strength of the two information sources and to the higher computational demands of context use relative to frequency (see especially, Kawamoto, 1993).

Given the different computational demands of using frequency and context information, age-related slowing is likely to affect these processes differently during ambiguity resolution. Myerson, Hale, Wagstaff, Poon, and Smith (1990) argued that cognitive slowing will have a greater effect on processes with more computational components than those with fewer components. Applying this argument to ambiguity resolution yields the hypothesis that cognitive slowing will have a greater effect on the complex processes of context use compared to activation of alternative senses of an ambiguity as a function of frequency. On this view, the degree to which older adults will use contextual information in a given situation could depend on a number of factors, including the degree of slowing in the participant sample, the nature of the ambiguity (such as the relative frequency of the alternatives), the strength of the context, and the time available to process the context. For example, the *pet store* context in the previous example occurred many words before the appearance of the ambiguous word *boxer,* and it is possible that even slower comprehenders would have sufficient time to process the context and bring this information to bear when interpreting the ambiguity. In other linguistic situations, however, there is less time to process the context. In the sentences *I saw the wooden match* and *I saw the tennis match,* for example, the context words *wooden* and *tennis* immediately precede the ambiguous word *match.* In this situation, slowed or inefficient comprehension processes might result in incomplete processing of the context in advance of the ambiguity.

Studies of aging and context use during language processing have yielded a variety of conflicting results. For example, Light and Capps (1986) and Morrow, Altieri, and Leirer (1992) found that compared to young adults, older adults had poorer context use in resolving referents of pronouns, but Leonard, Waters, and Caplan (1997) did not find such differences. Other studies have concluded that older adults benefit more from context than younger adults when the acoustic or visual signal is degraded (Pichora-Fuller, Schneider, & Daneman, 1995; Speranza, Daneman, & Schneider, 2000). Some of these different outcomes may stem from variations in experimental procedures. For example, Hopkins, Kellas, and Paul (1995) reported good use of context by older adults in resolving lexical ambiguities during sentence comprehension, but these researchers used a method in which the visual presentation rate of words in the sentences was calibrated individually for each participant, with generally much slower rates for the older participants than for the younger ones. It is not hard to imagine that when processing efficiency differences are minimized by changes in presentation rates, older and younger adults could show highly similar performance, whereas clear differences could emerge when both groups are tested with identical presentation conditions. Other differences across these studies may stem from differences in the stimulus materials, such as differences in the strength of context and the time available to process the context before some critical response is measured in the experimental paradigm. It is difficult to extract broad generalizations about the context manipulations in many studies, as the full set of materials is not always provided. However, examination of the stimulus materials that are available suggests that at least some degree of the different findings may rest in the distance between context information and the ambiguity in the materials. For example, the materials used by Pichora-Fuller et al. and Speranza et al. were designed to contrast high- and low-context conditions in identification of a sentence-final word, and the high-context sentences appear to contain many words related to the sentence-final target, as in *Tree trunks are covered with bark,* where the target *bark* is related to several interrelated words. These strong contexts may have tended to begin early enough that even slower comprehenders would have sufficient time to process them before the target was encountered. By contrast, the contexts used in Federmeier, McLennan, and De Ochoa (2002) seem more subtle. These researchers investigated event-related potential (ERP) responses to target words that fit the context to varying degrees. Consider the context: *The tourist in Holland stared in awe at the rows and rows of color. She wished she lived in a country where they grew …* Here the contextually appropriate word is *tulips,* a related but less expected word is *roses,* and a distantly related and unexpected word is *pines.* Federmeier et al. found that the ERP responses of both younger and older adults differed for highly predictable (*tulips*) versus unexpected (*pines*) words, suggesting that both groups were using contextual information to some degree. However, the young adults' ERP responses to the similar word (*roses*) were intermediate between responses to the highly predictable and unexpected words, suggesting that they were using context in a fine-grained way, whereas the older adults' responses did not differ for the two less predictable words (*roses* vs. *pines*). In other words, older adults do appear to use context to some degree but not to the extent that young adults do. It may be that the different results in Pichora-Fuller et al. versus Federmeier et al. stem from the relative strength of the contexts, or perhaps from the time course of context availability; note that in the *Holland* context previously mentioned, it becomes clear that the passage is about plants only at *grew,* the word immediately preceding the target. This analysis is quite speculative, because none of these studies attempted to manipulate or precisely control the context–ambiguity distance, and the studies use a variety of tasks and examine a large variety of ambiguities and context types.

We further explored these issues of cognitive aging and context use in ambiguity resolution, using both experiments and computational modeling. Experiments 1 and 2 investigated the lexical ambiguity resolution process when frequency and contextual information conflict and converge, respectively. Experiment 3 focused on the strength of the contexts and assessed younger and older adults' linguistic knowledge that formed the basis for the context manipulations used in Experiments 1 and 2. This experiment provided a measure of context strength for each item and the extent to which older and younger adults' responses in Experiments 1 and 2 were correlated with context strength. Experiment 3 also provided key data in the development of a simple connectionist model of ambiguity resolution and processing speed. This model tested the hypothesis that manipulation of a speed parameter could account for patterns of context use during ambiguity resolution.

3. Experiment 1

The approach described previously suggests that slowed or inefficient processing associated with aging would be most detrimental to context use in ambiguity resolution when there is very little time between encountering the context and the ambiguity in a sentence. We therefore developed sentences that required very rapid context–ambiguity integration and measured interpretation of the ambiguity immediately after it was presented in the sentence. Experiments 1 and 2 used a cross-modal naming task that has previously been shown to be sensitive to the time course of online processing during ambiguity resolution (Tyler & Marslen-Wilson, 1977). Participants were presented with an auditory sentence fragment that terminated with a lexically ambiguous word. At the offset of the ambiguous word, a visual target word disambiguating the ambiguity was presented on the computer screen. Participants named the visual target aloud, and naming time was measured. Although participants are making no judgment at this point concerning the relatedness of the target and the auditory fragment, naming times to the visual target have been shown to reflect the degree to which the target sensibly continues the auditory sentence fragment; these effects have been observed in studies with young adults (Tyler & Marslen-Wilson, 1977) and in healthy older adults and patients with mild to moderate Alzheimer's disease (Almor, Kempler, MacDonald, Andersen & Tyler 1999; Kempler, Almor, Tyler, Andersen & MacDonald, 1998). In the case of lexical ambiguity resolution, naming times are typically short when the visual target disambiguates the lexical ambiguity in favor of the meaning that the comprehender has adopted (on the basis of frequency of alternative meanings of the ambiguity, context, or both) and are typically long when the visual target favors the low-frequency or contextually inappropriate meaning, or both (Tyler & Marslen-Wilson, 1977). Because the visual target appears immediately after the ambiguity, and because of the automatic nature of the naming task, cross-modal naming can provide evidence for the earliest stages of ambiguity resolution.

Following the naming response, participants performed a second task indicating with a key press whether the visual target was a plausible continuation of the auditory fragment. This task not only encouraged the participants to attend to the auditory stimuli, it also provided some additional information concerning the time course of context use, in that the compatibility judgments were collected a few seconds after naming responses and thus might reflect a later stage of the ambiguity resolution process.

Stimuli were developed from sentences originally used in a reading study with young adults (MacDonald, 1993). These sentences contained ambiguous words such as *fires* and *guards* that have both a noun and a verb interpretation. This type of lexical ambiguity is useful in the cross-modal naming task because when the two meanings are members of different lexical categories (nouns and verbs), a subsequent visual target can provide a complete disambiguation of the ambiguity. For example, if the ambiguous word *fires* is followed by the visual target *us,* the sequence *fires us* is grammatical only if *fires* is interpreted as a verb; this visual target was used in Experiment 1.

All of the ambiguous words were more frequent in the noun interpretation than in the verb interpretation, so the *us* disambiguation assessed comprehenders' abilities to activate the low-frequency verb meaning. Visual targets always appeared immediately after the ambiguous word, so as to tap ambiguity resolution as early as possible. Semantic contexts promoting the noun or verb interpretation of the ambiguous word were also placed maximally close to the ambiguity to minimize the amount of time to process the context. The context manipulation affected only a single word immediately preceding the ambiguity, and an unambiguous condition was also included to provide a baseline.

With the disambiguating visual target always favoring the verb interpretation, and the frequency biases of the ambiguous words always favoring the noun interpretation, the extent to which comprehenders use context to arrive at the noun or verb interpretation of the ambiguity should be revealed in the pattern of naming or compatibility, or both, judgment responses. Good use of context should yield an Ambiguity × Context interaction, such that responses in the ambiguous condition with the helpful verb-supporting context should be similar to those for the unambiguous condition, whereas responses in the ambiguous condition with the misleading noun-supporting context should yield longer naming times or lower compatibility judgments, or both, compared to the unambiguous condition. A failure to use context should instead result in a main effect of Ambiguity, such that independent of context, the ambiguous conditions should yield longer naming times or lower compatibility judgments, or both, compared to unambiguous conditions.

3.1. Method

3.1.1. Participants

The young adult group was composed of 32 undergraduates at the University of Southern California (USC) who were either paid for their participation or received extra credit in a psychology course. All participants were native English speakers and were naive to the purpose of the experiment. Due to an experimenter error, the exact age and education was not recorded for 11 participants. Participation in the experiment was limited to individuals 30 years of age or under, and thus none of these 11 participants were over 30. For the remaining 21 participants, the mean age was 20.14 years, $SD = 1.74$, and the mean education was 13.38 years, $SD = 1.20$.

The older group was composed of 32 USC alumni who were compensated for participating. All participants were native English speakers, naive to the purpose of the experiment, and in reportedly good health. The mean age of the older participants was 73.0 years, $SD = 4.4$, with a mean 16.8 years of formal education, $SD = 2.0$.

3.1.2. Materials

The 16 experimental stimuli used in the cross-modal naming task were taken from materials used in Experiment 2 of MacDonald (1993; see Appendix B of that article). One item in the original stimuli containing the ambiguous word *accounts* was not grammatical with the *us* continuation and was replaced. Four versions of each stimulus sentence were constructed, manipulating the factors of ambiguity and context. An example of the stimuli is shown in Table 1.

Table 1
Example stimuli, Experiment 1

	Ambiguity
Auditory Fragment, Verb-Supporting Context	
The union told the reporters that the corporation fires	Ambiguous
The union told the reporters that the corporation could fire	Unambiguous
Auditory Fragment, Noun-Supporting Context	
The union told the reporters that the warehouse fires	Ambiguous
The union told the reporters that the warehouse could fire	Unambiguous

Note. The visual target was *us* in all conditions.

In the ambiguous conditions, the sentence fragments all ended with an ambiguous word that had both a plural noun and a third-person singular verb meaning (*fires, benefits, guards,* etc.). All ambiguous words had a higher frequency noun interpretation than verb interpretation; the mean was 6% verb interpretations in the Francis and Kucera (1982) corpus. The prior context for the ambiguous word was manipulated at two levels, verb supporting and noun supporting. These contexts differed by only one word, which immediately preceded the ambiguous word. The context manipulation affected the relative plausibility of the alternative interpretations of the ambiguous word. For example, *warehouse* promotes the noun interpretation of *fires* in the stimuli in Table 1 because it is more plausible for a warehouse to have a fire than to fire someone. The context word *corporation* creates the opposite bias, as it is more plausible for a corporation to fire someone than to have a fire. Note that these contexts become fully effective only when the ambiguous word is encountered. That is, there is nothing about the *warehouse* sentence context that is associated with something burning; it is only when the word *fires* itself is encountered that the conjunction of *warehouse* and *fires* conveys the noun sense of *fires.*

Whereas the contexts in the ambiguous condition modulated the relative plausibility of alternative interpretations, but never completely prohibited either alternative, contexts in the unambiguous condition added syntactic information to force the verb interpretation of the ambiguous word. Two changes were made to the ambiguous condition to form the unambiguous condition. First, the final *s* on the ambiguous word was deleted, yielding *fire, guard, benefit,* etc. Second, the word *could* was added between the context word and the ambiguous word, so that the ambiguous *corporation* or *warehouse fires* became *corporation could fire* and *warehouse could fire.* Following the word *could,* the only grammatical interpretation of *fire* is the verb interpretation. The unambiguous condition thus represents a case of an overwhelmingly strong syntactic context, in contrast to the plausibility-biased semantic contexts in the ambiguous condition.

An additional 64 filler and 5 practice sentence fragments were constructed; 24 of the fillers were from an unrelated experiment. All of the filler items used visual target items other than the word *us.* Two other visual targets (*their* and *street*) were repeated across 10 filler items each, so that repetitions of visual targets were not limited to *us.*

Stimuli were recorded by the first author and digitized at 22 KHz using MacRecorder software. Each stimulus file was edited so that it terminated at the offset of the ambiguous word (or some other word in the filler items). Special care was taken to record the ambiguous phrases with a neutral intonation that did not promote a particular interpretation of the ambiguous word. To check the intonation, one judge who was naive to the purpose of the experiment examined the sound waveforms and measured the duration of the final word of the experimental items; word duration is a major component of intonation at the boundaries between noun and verb phrases (Cooper & Paccia-Cooper, 1980). There were no differences in final word duration across these four conditions, $F < 1$.

3.1.3. Procedure

Younger and older participants were tested individually in a quiet room at USC. The cross-modal task was conducted on a Macintosh IISE computer. Auditory sentences were presented over an external speaker that participants adjusted to a comfortable sound level. All participants reported that they were able to hear the stimuli clearly. Participants were seated in front of the computer at a distance from which they could comfortably read the computer screen. A table microphone and button box were situated in front of the computer screen. The microphone was linked to a voice-activated relay connected to the computer via the button box.

Instructions were presented on the computer screen and were discussed with each participant. When it was clear that the participant understood the instructions, the 5 practice trials were presented, followed by the 80 experimental and filler trials in random order. Each trial began with the presentation of a fixation cross on the screen. The auditory presentation of the sentence fragment began 1 sec after the cross appeared; the cross remained on during the presentation of the sentence fragment. At the acoustic offset of the fragment, the cross was removed and a visual target word appeared on the computer screen; that is, there was a 0 msec interstimulus interval (ISI) between the acoustic stimulus and visual target. Participants named the visual target word aloud as quickly and accurately as possible. Naming responses to the visual target word triggered the voice relay, and the visual target word was removed from the computer screen. The experimenter recorded whether the naming response was correct or unusable, either because the participant misread the target, the naming response failed to trigger the voice key, or because the voice key was triggered by some extraneous sound such as a cough. A question was then presented on the computer screen either concerning information in the auditory sentence or asking whether the visual target was a good continuation of the auditorily presented sentence (always the latter type of question for the experimental items). Participants pressed a key marked *Yes* or *No* on the button box to answer the question and did not receive any feedback. Presentation of the next trial was initiated by participants with a key press so that participants could take breaks between trials if desired. Each experimental session lasted no more than 45 min.

3.2. Results

3.2.1. Naming times

Prior to statistical analysis, all unusable naming times were removed. The naming data were then trimmed in a two-step procedure. First, all naming times greater than 5,000 msec were removed, with the view that these trials reflected a failure of the naming response to trigger the voice key but had been missed by the experimenter, and second, all times more than 3 *SD* above or below a participant's mean naming time were removed. A total of 2% of the data for the younger participants was removed, and 6% of the data was removed for the older participants.

Each participant's naming times were transformed to z scores to correct for differences in mean response time (RT) and variability between the two groups. These transformed times are shown in Fig. 1, and the untransformed scores are shown in Appendix A. An analysis of variance (ANOVA) performed on the transformed data revealed a significant three-way interaction between ambiguity, context, and age, $F(1, 62) = 4.63$, mean square error [MSE] = 1.28, $p < .05$ (generalization across items is investigated in Experiment 3, and analyses with items as a random effect are presented there). The nature of this interaction was that younger participants' naming times demonstrated an effect of context, whereas those of the older participants did not. The younger group's naming times yielded a reliable Ambiguity × Context interaction, $F(1, 31) = 16.15$, $MSE = 3.46$, $p < .0001$. For this group, naming times in the verb-supporting context did not vary as a function of ambiguity, $F < 1$, but in the noun-supporting context, nam-

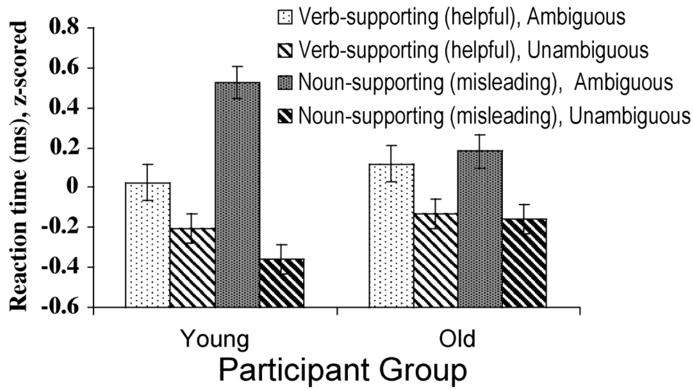

Fig. 1. Younger and older adults' normalized naming times to the visual target *us* as a function of ambiguity and context. The verb-supporting context is the helpful context in this study.

ing times in the ambiguous condition were significantly longer than in the unambiguous condition, $F(1, 31) = 49.60$, MSE = 12.56, $p < .0001$, and also longer than in the ambiguous verb-supporting condition, $F(1, 31) = 12.11$, $MSE = 4.05$, $p < .01$. This pattern replicates the reading data from younger adults in MacDonald (1993) and is the pattern that is predicted with good use of context. By contrast, the older group's naming times did not yield an Ambiguity × Context interaction, $F < 1$. There was also no effect of context, F < 1. Instead, a main effect of ambiguity was obtained, such that older participants' naming times were significantly longer in the ambiguous conditions than in the unambiguous conditions, independent of context $F(1, 31) = 8.12$, $MSE = 2.78$, $p < .01$.

3.2.2. *Compatibility judgments*

The compatibility judgments for younger and older participants are shown in Fig. 2. The compatibility judgment analyses were conducted on only those experimental trials in which

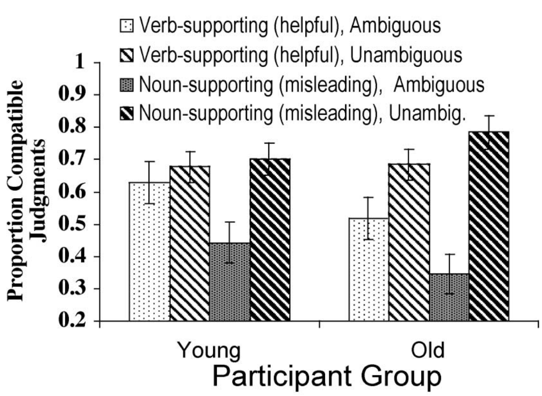

Fig. 2. Younger and older adults' judgments of compatibility between auditory stimulus and the visual target *us* as a function of ambiguity and context. The verb-supporting context is the helpful context in this study.

the corresponding naming response had been included in the naming-time analysis; the results did not change when the analysis of the compatibility judgments was performed over all data (including trials with microphone errors, trimmed RTs, etc.).

In contrast to the naming task, analysis of the compatibility judgments did not reveal an Ambiguity × Context × Age interaction, nor was there a main effect of age, Fs < 1. There was, however, a significant Ambiguity × Context interaction, $F(1, 62) = 13.387$, $MSE = .92$, $p < .001$, such that both younger and older adults judged targets to be compatible in the verb-supporting context about equally often at both levels of ambiguity, $F < 1$, but in the noun-supporting context, both groups judged targets to be compatible with the preceding context less often in the ambiguous condition than in the unambiguous condition, $F(1, 63) = 38.53$, $p < .001$. This pattern of results is similar to that found in the naming data for younger adults and reflects good use of context by both older and younger adults on this task.

3.3. Discussion

The materials in Experiment 1 were designed such that use of context in ambiguity resolution would be revealed by an Ambiguity × Context interaction, whereas a failure to use context would result in a main effect of ambiguity, with no interaction with context. The Ambiguity × Context interaction was found in the compatibility judgments for both age groups, but only the younger group's naming times yielded the interaction; the older group's times showed only the main effect of ambiguity. One interpretation of this pattern of results is that all participants were eventually able to use the context, but younger adults were able to use the context more rapidly than older adults to resolve the ambiguity. This interpretation is consistent with a slowing or processing efficiency account of cognitive aging and the claim that more complex processes (here context use) will be more affected by cognitive slowing than simpler processes (use of frequency information; Myerson et al., 1990).

Alternative interpretations of these data are possible, however, because the cross-modal naming and compatibility judgment tasks vary not only in the amount of time they allow for context use, but also in their task demands (see Balota et al., 2001, for discussion of task effects and aging in ambiguity resolution). The age differences observed in Experiment 1 might be due to the nature of the tasks, and not to different time courses of context use in younger and older adults. For example, it is possible that the cross-modal naming task interfered with or obscured the older adults' use of context, perhaps because some participants did not understand the importance of naming the target rapidly, because they began to decide on the compatibility judgment response before naming the target aloud, because they had difficulty speaking into the microphone, because they had difficulty reading the visual target on the computer screen, or all of these. The older group did have substantially longer naming times compared to the younger group (see Appendix A), but there are several reasons not to attribute all of the effects in Experiment 1 to this alternative explanation. First, no older participant claimed to have any problems performing the naming task. More important, cross-modal naming times indicated that the older adults were able to use the syntactic context in the unambiguous condition to resolve the ambiguity. Recall that the unambiguous condition had the form *the warehouse* or *corporation could fire …* , in which the last word (e.g., *fire*) was still ambiguous between a noun and a verb, but the presence of *could* in the prior context made only the verb interpretation grammatical. The older group's naming responses to the visual target *us* were significantly shorter in this unambiguous condition compared to the ambiguous condition, indicating that they were sensitive to the strong prior context here. Experiment 2 pursues these issues further, both with methodological changes to the cross-modal paradigm and with a change in the visual target word. These changes will allow us to assess interpretation of the ambiguity in favor of the high-frequency noun interpretation instead of to the low-frequency verb interpretation that was assessed in Experiment 1.

4. Experiment 2

In Experiment 2, several changes were made to the materials and procedure from Experiment 1 to meet two goals: (a) make the cross-modal naming task as easy as possible for older participants, so as to increase the chances of finding evidence of semantic context use in the early stages of ambiguity resolution in this sample; and (b) begin to explore the effects of frequency on ambiguity resolution in older participants.

To begin to investigate frequency and context use, we changed the visual target for the experimental items to the word *could,* which disambiguated the ambiguity in favor of the high-frequency noun interpretation rather than the low-frequency verb interpretation as in Experiment 1. Both the ambiguous noun-supporting (e.g., *warehouse fires*) and ambiguous verb-supporting (e.g., *corporation fires*) context conditions from Experiment 1 were used. With the change in visual target, the noun-supporting context (e.g., *warehouse fires*), which had been misleading in Experiment 1, was now the helpful context that promoted the interpretation that was revealed at the disambiguation. The verb-supporting context, which was the helpful context in Experiment 1, became the misleading context in Experiment 2.

Based on the results of Experiment 1, we predicted that both older and younger adults' compatibility judgments would show the influence of context, as would younger adults' naming-time data. Good use of context in this experiment would be indicated by a pattern in which naming times–compatibility judgments to the visual target *could* in the noun-supporting context (e.g., *warehouse fires*) was similar to an unambiguous condition, but targets following a verb-supporting context (*corporation fires*) would yield longer naming times and fewer compatibility judgments than in the unambiguous condition.

The older adults' naming times should reflect their ability to use both context and frequency information to resolve ambiguity. Three alternative results are plausible. First, if older adults' use of context in the Experiment 1 naming task was obscured by their difficulty with the task, and if the task is sufficiently easier in Experiment 2, then older adults should show better use of context here, yielding a pattern of naming times similar to the younger participants' data. Second, if older adults rapidly use only frequency and not context information during ambiguity resolution, then they should adopt the high-frequency noun interpretation of the ambiguity in both ambiguous conditions, independent of context. In this case, the visual target should form a good continuation of the auditory fragment in both ambiguous conditions, and all ambiguous naming times should not differ from the unambiguous condition. A third alternative is that older adults may not be able to settle on any interpretation of the ambiguous words, creating higher processing loads as they try to bring information to bear to resolve the ambiguity. If so, then both ambiguous conditions could yield longer naming times than in the unambiguous condition.

4.1. Method

4.1.1. Participants

All participants were native English speakers and were naive to the purpose of the experiment. The younger group was composed of 32 USC undergraduates who were paid for their participation. Their mean age was 23.1 years, *SD* = 5.6, and they reported a mean of 15.4 years of formal education, *SD* = 2.7.

The older group was composed of 32 community-dwelling USC alumni who reported themselves to be in good health. All were paid for parking and travel expenses. The mean age of the older participants was 72.0 years, *SD* = 4.8, with a mean 16.0 years of formal education, *SD* = 2.0.

4.1.2. Materials

The disambiguating visual target word was changed from *us* to *could,* which forced the noun interpretation of the ambiguity; for example *warehouse fires could …* is grammatical only if *fires* is a noun. This change necessitated a change in the unambiguous condition. It was not possible to fully cross the ambiguity manipulation with the context manipulation as in Experiment 1, because there is no prior syntactic context that forces phrases such as *warehouse* or *corporation fires* to be interpreted unambiguously as noun phrases. Instead, one unambiguous condition was included in the design, in which the context noun (e.g., *warehouse* or *corporation*) was replaced by a one-word adjective context (e.g., *dangerous*). Because only a noun or another adjective may follow an adjective in English, the presence of the adjective before a noun or verb ambiguity such as *fires* forced the noun interpretation of the ambiguity. The context adjectives were chosen to be similar in length to the context nouns from the ambiguous conditions, and adjectives that were very closely associated with the ambiguous word were avoided, to make the stimuli comparable in plausibility to the ambiguous conditions. There were thus three levels of the context factor, unambiguous (adjective context), helpful noun supporting, and misleading verb supporting.

The experimental stimuli consisted of the 16 experimental items used in Experiment 1, supplemented with 8 new items to increase power and balance items across the three cells in this experiment. As with the original 16 items, the 8 new items contained noun–verb ambiguities that were more frequent in the noun than the verb interpretation; the mean was 93% noun interpretations in the Francis and Kucera (1982) corpus. An example of the stimuli may be seen in Table 2.

Thirty-eight filler and 5 practice sentences were constructed; 18 of the fillers were experimental items from an unrelated experiment. All filler items used either the visual target *could* or *by,* so across all experimental and filler items, 55% of the targets were *could* and 45% were *by.*

The stimuli were recorded and digitized as in Experiment 1. Analyses of the duration of the ambiguous word in the experimental items showed no differences in duration across the three experimental conditions, $F < 1$.

Table 2
Example stimuli, Experiment 2

Context	Auditory Fragment
Verb-supporting	The union told the reporters that the corporation fires
Noun-supporting	The union told the reporters that the warehouse fires
Unambiguous (adjective)	The union told the reporters that the dangerous fires

Note. The visual target was *could* in all conditions.

4.1.3. Procedure

The procedure was identical to that in Experiment 1 except for several small changes designed to elicit the best performance from older subjects. First, the visual target words were presented in a larger font than in Experiment 1, and the importance of rapid naming responses and speaking into the microphone was stressed repeatedly in the instructions to all participants. In addition, the auditory fragment–visual target compatibility judgment task was presented after every stimulus item in Experiment 2, whereas some filler items in Experiment 1 had been followed by comprehension questions about the auditory sentence rather than the compatibility judgment.

4.2. Results

4.2.1. Naming times

Prior to statistical analysis, all unusable naming times were removed. The naming data were then trimmed in the two-step procedure performed in Experiment 1, affecting 0.05% of the data for the younger participants and 3.8% of the data for the older participants. The percentage of usable data was higher for both age groups in this experiment compared to Experiment 1. Moreover, the raw mean RTs of the older group (1,189 msec) were substantially shorter than for the older group in Experiment 1 (1,658 msec). The raw means for the young adults in this study (639 msec) were also slightly shorter than in Experiment 1 (679 msec); see Appendix B for all cell means. Although comparisons across different samples and different visual targets are certainly not definitive, these patterns suggest that the methodological changes in Experiment 2 stressing the importance of the naming task were effective in directing all participants' attention to this task, especially that of the older adults.

The z score transformed naming times for younger and older participants in the three experimental conditions are shown in Fig. 3. An analysis of variance on the z scores of the naming times revealed a significant Age × Context interaction, $F(2, 124) = 3.30$, $MSE = .75$, $p < .05$. For the younger group, there was a reliable effect of context, $F(2, 62) = 7.99$, $MSE = 1.23$, $p < .05$. The pattern of naming times reflected the predicted good use of context for this group: When the context supported the noun interpretation of the ambiguity, naming times were no different than times in the unambiguous condition, $F < 1$, but naming times in the verb-supporting context were 47 msec longer than in the unambiguous condition, a reliable difference, $F(1, 31) = 9.51$, $MSE = 2.18$, $p < .01$. By contrast, there were no differences in the older group's naming times across the three experimental conditions, $F < 1$. This result is the pattern that is expected if comprehenders were sensitive to the relative frequency of the alternative interpretations but not sensitive to contextual information.

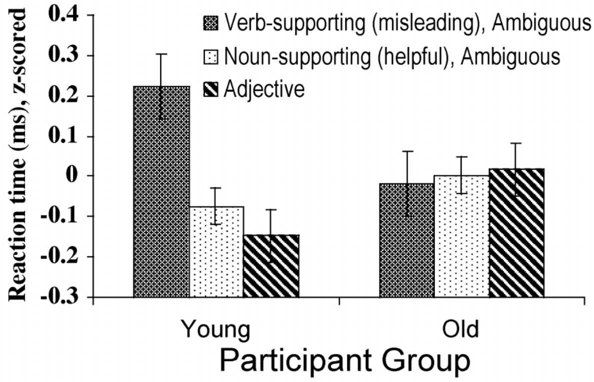

Fig. 3. Younger and older adults' normalized naming times to the visual target *could* as a function of context. The noun-supporting context is the helpful context in this study.

4.2.2. Compatibility judgments

The compatibility judgment analyses were conducted on those experimental trials for which the corresponding naming response had been included in the naming-time analyses. As in Experiment 1, the results did not change when trials removed from the naming-time analysis (e.g., microphone errors) were included in the compatibility judgment analysis. These data are shown in Fig. 4.

The pattern of responses for both age groups was consistent with that found in Experiment 1. An omnibus analysis revealed neither an Age × Context interaction nor a main effect of age, *F*s < 1. There was, however, a significant main effect of context, $F(2, 124) = 12.47$, $MSE = .07$, $p < .0001$. Pairwise comparisons across age showed that in the helpful noun-supporting context, the percentage of visual targets judged as compatible was no different from that in the unambiguous condition, $F < 1$, but the unhelpful context that promoted the verb interpretation yielded a significantly lower percentage of compatible judgments than in the unambiguous

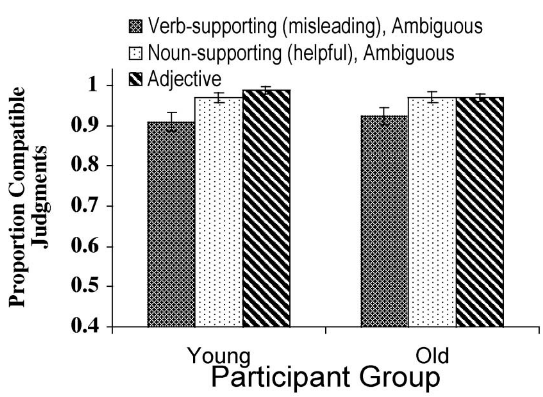

Fig. 4. Younger and older adults' judgments of compatibility between auditory stimulus and the visual target *could* as a function of context. The noun-supporting context is the helpful context in this study.

condition, $F(1, 63) = 17.96$, $MSE = .12$, $p < .001$. Thus as in Experiment 1, both groups showed reliable effects of context in their compatibility judgments.

4.3. Discussion

In Experiment 2, the younger adults showed the pattern of naming times that reflected good use of context, and both younger and older adults showed patterns of compatibility judgments that reflected good use of context, all replicating the patterns found in Experiment 1. The older group's naming times, however, showed no differences between any of the three conditions. Although caution is necessary when interpreting null results, this pattern is consistent with the hypothesis that older adults relied only on frequency during the initial stages of ambiguity resolution. When frequency information was misleading and promoted the wrong interpretation of the ambiguity in Experiment 1, this group's naming times were uniformly longer in ambiguous conditions compared to unambiguous conditions. When frequency information was helpful in Experiment 2, however, this effect of ambiguity disappeared in the older adults' naming data.

By contrast, the effect of ambiguity in compatibility judgment data was clear for both younger and older adults. Thus across two experiments, the younger and older adults show the same pattern of performance on the compatibility judgments but different patterns in the cross-modal naming task. This pattern of results is the pattern that is expected if slowed language processing in older adults prevents these comprehenders from using contextual information as rapidly as younger comprehenders can.

An alternative interpretation that has not yet been considered is that the semantic contexts used in these experiments were not equally biasing for the younger and older adults. That is, younger and older adults differ not only in the speed with which they process language but also in their breadth of experience with language and in their general world knowledge. We have emphasized that contexts are often ambiguous themselves and vary widely in both the strength of their constraint and the point at which the constraining information arrives. Thus a context that exerts a strong plausibility bias for one age group might not have the same effect for the other age group.

One way to investigate this possibility is to assess the strength of the contextual bias for each stimulus item in samples of younger and older adults, using a method that does not depend on rapid processing. A positive correlation between a measure of context strength in the young and old would indicate that both age groups have similar knowledge relevant to the contexts, and both groups find the contexts similarly biasing. Given this assessment of context strength for each item in both noun-supporting and verb-supporting conditions, it would then be possible to examine the extent to which context strength predicts naming times and compatibility judgments in the two age groups in Experiments 1 and 2. Experiment 3 collects measures of context strength and brings them to bear on the data in Experiments 1 and 2.

5. Experiment 3

This experiment assessed the strength of contextual bias for the various stimulus items with an untimed sentence completion task. In this task, younger and older adults read the sentence fragments that had been presented in the previous experiments, which ended at the ambiguous word, and then they wrote completions for the fragments. Because the alternative interpretations of the ambiguous words were from different lexical categories (noun vs. verb), participants' completions of the sentence fragments clearly indicated how they interpreted each ambiguous word. For example, for the fragment *The prospective students were informed that the fraternity houses … ,* an 83-year-old respondent provided the completion *were located near private homes.* This completion indicated that the respondent had interpreted the ambiguous word *houses* as a noun. The completion task was conducted twice on different groups of younger and older participants, once using the experimental materials from Experiment 1 and once using the larger set of items from Experiment 2.

5.1. Method

5.1.1. Participants

The sentence completion materials for the Experiment 1 fragments was mailed to 80 older USC alumni who had not participated in the previous experiments. Forty-four of the response sheets were returned, five of which were not included because the respondents reported that their native language was not English. The mean age of the remaining 39 respondents was 74.5, *SD* = 7.0; 69% were women. The younger group was composed of 96 native English-speaking students in an introductory psychology course who completed a sentence completion task similar to that of the older respondents as part of a course assignment, as reported in MacDonald (1993). Age and sex data for the younger respondents were not recorded.

The sentence completion task for the Experiment 2 items was mailed to 60 older USC alumni who had not participated in the previous experiments. Twenty-six of the sentence completions were returned. All older participants reported that their native language was English. The mean age of the older respondents was 73.1, *SD* = 4.5; 42% were women. The younger group was composed of 163 native English-speaking students who completed the task for extra credit in an introductory psychology course. The mean age of the younger respondents was 18.8, *SD* = 1.2; 64% were women.

5.1.2. Materials and procedure

The sentence completion tasks for Experiments 1 and 2 were adapted from the task used by MacDonald (1993). Each respondent received a response sheet consisting of a series of sentence fragments for which respondents were instructed to write a completion. Two examples of unambiguous sentence fragments with simple, plausible completions were provided in the instructions. Respondents were encouraged to complete the sentence fragments with the first ending that occurred to them, and it was stressed that there were no right or wrong answers.

The critical items on each response sheet were the ambiguous experimental items. These were identical to the sentence fragments that had been presented auditorily in Experiments 1 and 2, ending with the lexical ambiguity, for example, *The union told the reporters that the warehouse fires …* Unambiguous versions of the items were not tested. A large number of filler items, without lexical ambiguities, were included in the response sheets to limit the chance that the participants would become aware of the ambiguities. Each response sheet for the Experiment 1 items contained four verb-supporting items and four noun-supporting items, intermixed with 19 filler fragments of the same length as the experimental items. Eight different response sheets were used across participants, and each respondent saw half of the experimental items. To accommodate the addition of new experimental items from Experiment 2, each version of the response sheets for these items contained six verb-supporting and six noun-supporting items, intermixed with 23 filler fragments. Again there were eight different response sheets, and each respondent saw half of the experimental items. On all response sheets, experimental items were always separated by at least two filler items. Two response sheets in this set each had one additional experimental item, the noun- and verb-supporting versions of an experimental item from Experiment 1, which had replaced an original item in MacDonald (1993) that was incompatible with the cross-modal naming target.

5.1.3. Scoring

Older and younger respondents' sentence fragment completions were scored by a research assistant blind to the hypotheses in this work. Each completion was scored for whether it reflected either a verb or noun interpretation of the ambiguous word. With the exception of two illegible responses, all completions clearly implicated a noun or verb interpretation of the ambiguity.

The dependent variable was the percentage of verb completions provided in each age group in noun-supporting and verb-supporting conditions. Because each respondent saw only half of the items, we report analyses with stimulus item ($n = 16$ in the Experiment 1 materials and $n = 24$ in Experiment 2 materials) as the random factor, with context and respondent age as within-item factors in ANOVAs. In correlations, both noun- and verb-supporting items were used together, yielding 32 data points for each age group in Experiment 1 and 48 in Experiment 2.

5.2. Results

5.2.1. Older versus younger adults' sentence completions

The mean percentages of sentence completions with the verb interpretation are shown in Table 3. As is clear from the table, both age groups were strongly influenced by the contexts, in that across both sets of materials, the percentage of verb completions was 11% in the noun-supporting context versus 59% in the verb-supporting context. An analysis of the Experiment 1 materials showed a large effect of context, $F(1, 15) = 97.16$, $MSE = 375.06$, $p < .001$, but no effect of age ($F < 1$) and no interaction of the two factors, $F(1, 15) = 1.65$, $MSE = 179.40$, $p > .20$. Analysis of the Experiment 2 materials also yielded an effect of context, $F(1, 23) = 109.79$, $MSE = 523.71$, $p < .001$. There was also an effect of age, reflecting the fact that across both levels of context, older adults produced slightly more completions with the verb interpretation than did younger adults (40% vs. 33%, respectively), $F(1, 23) = 5.99$, $MSE = 186.68$, $p < .05$, but there was no interaction between the two factors, $F(1, 23) = 1.77$, $MSE = 242.21$, $p = .20$.

We next correlated the young adults' percentage of verb completions for each item and each context with those of the older adults to determine whether both groups were similarly affected by the context in individual fragments. A strong positive correlation was found between older and younger respondents' completions, for both the Experiment 1 materials, $r(31) = .88$, $p < .001$, and the Experiment 2 materials, $r(47) = .83$, $p < .001$. These results demonstrate that the stimulus items that had particularly strong contexts for the younger adults tended to be the same ones that were strongly biasing for the older adults.

Table 3
Percentage and standard deviations of sentence completions with verb interpretation of ambiguous word

	Materials	
	Noun-Supporting Context	Verb-Supporting Context
Experiment 1		
Younger adults	11.87 (18.51)	55.28 (27.68)
Older adults	8.39 (14.94)	60.42 (28.18)
Experiment 2		
Younger adults	10.91 (13.68)	55.63 (28.71)
Older adults	13.51 (25.85)	66.68 (26.21)

Note. Percentages given are item means. Standard errors given in parentheses.

5.2.2. *Comparisons with naming time and compatibility judgment data*

We next investigated whether younger and older respondents' sentence completions predicted the naming and compatibility judgment data for each age group in Experiments 1 and 2. Younger respondents' percentage of verb completions evidenced a strong negative correlation with the younger adults' naming times for Experiment 1, $r(31) = -.59$, $p < .001$, such that those fragments with the strongest verb-promoting contexts had the shortest naming times to the visual targets that forced the verb interpretation of the ambiguity. Similarly, for the Experiment 2 data, the percentage of noun completions (100 minus percentage verb completions) were negatively correlated with the naming times to the noun-forcing target in that experiment, $r(47) = -.42$, $p < .01$. Thus the sentence completion data were a good predictor of young adults' naming times in both Experiments 1 and 2. By contrast, the older respondents' completion data did not correlate with the older adults' naming times in either Experiment 1, $r(31) = -.03$, *ns,* or Experiment 2, $r(47) = .19$, *ns.*

As with naming times, younger participants' compatibility judgments from Experiment 1 were strongly correlated with context strength, $r(31) = .44$, $p < .05$, such that high rates of verb-sentence completions were associated with high rates of "compatible" judgments for the verb-forcing target in Experiment 1. A similar result appeared with the Experiment 2 data; the rate of noun completions was positively associated with the rate of compatible judgments for noun-forcing visual targets, $r(47) = .45$, $p < .01$. The older respondents' sentence completion data were similarly positively correlated with the older adults' compatibility judgments in both Experiment 1, $r(31) = .46$, $p < .01$ and Experiment 2, $r(47) = .39$, $p < .01$. Thus in contrast to the naming data, the strength of context measures collected in Experiment 3 did predict older adults' fragment-target compatibility judgments in Experiments 1 and 2.

5.3. *Discussion*

The important results from this study were first that younger and older respondents' sentence completions for both Experiment 1 and Experiment 2 items were strongly correlated with each other, indicating that the contexts induced similar plausibility biases in the two age groups. Second, context strength data were strongly correlated with the younger adults' naming time and compatibility judgment data as well as older adults' compatibility judgments, demonstrating that stronger contexts led to shorter naming times to disambiguating visual targets and more "compatible" judgments for those targets. Thus across sentence completions, compatibility judgments, and cross-modal naming data, the younger and older adults look identical in their use of context in ambiguity resolution in every measure except in the cross-modal naming data, where older adults' performance does not indicate good context use. This pattern of results suggests that although older participants possessed knowledge of the plausibility bias created by the context word, they were unable to use the biasing context to resolve ambiguity within the time captured by cross-modal naming. Because older adults were able to use the stronger syntactic context in the unambiguous condition in Experiment 1, the sum of the naming, compatibility judgment, and sentence completion data suggests that older adults' ability to use context is a function of both the strength of the context and the time available to integrate context and ambiguity. We next pursued this approach within a computational model in which we simulated ambiguity resolution in old versus young comprehenders through the manipulation of a single speed parameter that modulated the speed of all processing operations in the model. If this manipulation of speed in the model captures the performance of younger and older adults, this result would provide evidence for the viability of a slowing account of language comprehension.

6. A computational model

We developed a dynamical model that used frequency and context information over time to resolve the ambiguities tested in the experiments. We used the models in two simulations, with two different goals. The first simulation was designed to be an existence proof of the claim that variation in processing speed could modulate context use in ambiguity resolution, even when all else is held constant. To foreshadow our results slightly, we found that we could successfully simulate older versus younger adults' context use in ambiguity resolution through manipulation of a single speed parameter controlling activation of all nodes in the model, and this outcome led to a second goal, addressed in Simulation 2. In this simulation, we sought to go beyond the exact conditions tested in our experiments and to use the model to map out a large space of processing speeds and available time to integrate context with the ambiguous word. The results of this simulation suggest how these two factors may jointly contribute to context use, potentially illuminating inconsistent results in previous studies and suggesting avenues for new research.

In implementing the model used in both simulations, we focused on the conditions of Experiment 1, which fully crossed ambiguity and context, and where frequency information and context information were in conflict in promoting an interpretation of an ambiguity. The model was designed to simulate three crucial stages of processing in this experiment: (a) It was presented with a context (e.g., *warehouse, corporation,* or an unambiguous context such as *warehouse could*) and activated nodes representing this context; (b) it was presented with an ambiguous word (e.g., *fires*) and activated the noun and verb meanings to varying degrees, as a function of their relative frequency and the nature of the preceding context; and (c) it was presented with the disambiguating word *us* and activated a node representing that word as a function of the activation levels of the other nodes that had been activated in Stages 1 and 2. The dependent variable, which we compared with the naming times in Experiment 1, was the time it took for the activation level of the *us* node to reach a threshold value. The model contained one global speed parameter, α, which controlled the speed with which information was passed between all nodes in the network. This speed parameter was designed to reflect the overall differences in processing speed that are hypothesized to exist in the younger and older adults. Our prediction is that variations in this speed parameter will modulate the extent to which the model's interpretations of the ambiguity are constrained by context and frequency of the alternative interpretations. The parameters of context strength, frequency, and other values were hand-set for each stimulus item in Experiment 1-based sentence completion data and frequency norms (see McRae, Spivey-Knowlton, & Tanenhaus, 1998, for a similar approach, and Lindfield & Wingfield, 1999, for another simulation of cognitive slowing).

6.1. Model architecture

The model consisted of a set of nodes and weighted connections between them. The model employed a localist representation, in that each element in the model was represented by a single node. A picture of the model's architecture can be seen in Fig. 5.

The noun and verb interpretation of the ambiguous words from Experiment 1 were modeled with two nodes, one for each interpretation of the ambiguity. The noun- and verb-supporting contexts (e.g., *warehouse, corporation*) were modeled by a pair of nodes, which excited and inhibited the respective noun or verb sense of the ambiguous word-interpretation nodes. The unambiguous condition (e.g., *warehouse could fire*) was modeled using the context nodes plus

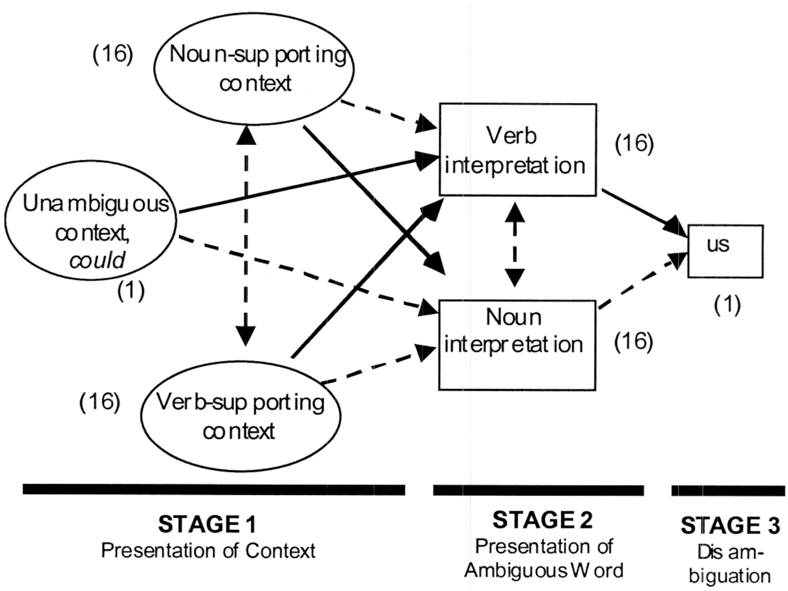

Fig. 5. Diagram of the computational model simulating the effect of processing speed on context use in Simulations 1 and 2.

one additional node for *could* that reflected the syntactic information that forced the verb-interpretation of each ambiguous word. The visual target *us* was represented by one node.

6.1.1. Connections between nodes

The nodes were connected to one another via excitatory connections, shown with continuous lines in the figure, or inhibitory connections, shown with dashed lines. For example, the verb-supporting context (e.g., *corporation*) excited the verb-interpretation node and inhibited the noun-interpretation node, whereas the noun-supporting context (e.g., *warehouse*) excited the noun-interpretation and inhibited the verb-interpretation node. The two context nodes also mutually inhibited each other, through a winner-take-all competition scheme detailed later. The magnitude of these excitatory and inhibitory connections was set to +1.0 and –1.0, respectively.

The actual inputs to the context nodes, for simulating each trial, were derived from the sentence completion data reported in Experiment 3 here and in MacDonald (1993). For example, the sequence *corporation fires* was completed with the verb interpretation 63% of the time by young adults, and the noun interpretation 37% (see Appendix B of MacDonald, 1993). This constraint was realized in the model by first computing the difference between the proportion of verb completions for each word and the overall mean proportion of verb completions. The z score of these numbers was computed, and the input to the verb-supporting context node was set to that (positive or negative) z score. Similarly, the input to the noun-supporting context node was set to the negative of this z score. Fragments in the verb-supporting condition (e.g., *corporation fires*) had a mean input of 1.2 to the verb-supporting context node and –1.2 to the noun-supporting context node. For the noun-supporting condition (e.g., *warehouse fires*), there was a mean input of –0.39 to the verb-supporting context node and 0.39 to the noun-supporting context node. Note that we did not use different completion data to set the context nodes for simulations of old versus young performance but used only one set of completions to simulate both groups. This reflects our hypothesis that processing efficiency, not knowledge about the contexts, drives the differences between old and young adults in our studies. The simulations were performed both with the context values derived from young adult sentence completions (MacDonald, 1993) and with the highly similar values obtained from older adults' completions (Experiment 3 here). The results were essentially identical; only the model results based on young adult completions are presented here.

To simulate the unambiguous condition from Experiment 1 (e.g., *corporation could* or *warehouse could*), an additional syntactic constraint node was activated. This node's activity influenced the interpretation nodes for the ambiguous word through strong weights: –2.0 to the noun-interpretation node and +2.0 to the verb-interpretation node. The *could* node was clamped to zero for ambiguous conditions.

Inputs to the interpretation nodes for the ambiguous words (e.g., *fires*-noun versus *fires*-verb) were set according to the frequency biases for these words (Francis & Kucera, 1982; values for each word are reported in Appendix B of MacDonald, 1993). For example, the word *fires* was used as a verb 29% of the time in the Francis and Kucera corpus, so on presentation of a fragment containing *fires,* input to the verb-interpretation node was set to 0.29, and input to the noun-interpretation node was set to 0.71. Across all items, the mean excitation to the verb-interpretation node was 0.08, and 0.92 for the noun-interpretation node, reflecting the strong noun bias for these lexically ambiguous words.

The interpretation nodes for the ambiguous word were connected to the *us* node. The noun-interpretation node inhibited activation of the *us* node with a weight of –1.0, whereas the verb-interpretation node excited the *us* node with a weight of +1.0.

6.1.2. Node output and competition

For each time sample, each node computed its output potential *o* from its aggregate input *x* according to the following differential equation: $\frac{\partial o}{\partial t} = \alpha(x - o)$, such that the rate of change of output (*o*) is proportional to the difference between this output and the input (*x*). The global speed parameter α controlled the speed of each unit. This parameter was fixed for all nodes in the network. A node began to "fire" whenever its potential output was greater than zero. Nodes that were "firing" influenced other nodes that they were connected to according to the weight between the nodes. In simulations corresponding to older adults, we used a small value of α such that each unit changed slowly, and for simulations of younger adults, a larger value was used so that the units changed more rapidly. These values were chosen through experimentation with the network; a continuous range of speed values and their consequences are explored in Simulation 2.

The context nodes were built as competing nodes; that is, they have additional computational machinery such that they implement a winner-take-all competition scheme. The two interpretation nodes also had this competition scheme. The general nature of this competition is to guarantee that whichever of the two competing nodes receives more activation will ultimately be firing in the steady state, and the node receiving less activation will not. The time for the competition to resolve depends on the difference in the input strength to each unit. For example, if one unit receives an input of 0.9 and the other receives 0.1, the winner will quickly accrue a greater than zero level of activation and begin firing; if the respective activations are 0.51 and 0.49, it will take much longer for the winner to begin firing. Hence, the ability to resolve an ambiguous situation is a function of the relative strengths of the inputs to the competing elements and the speed of processing of the units. See Appendix C for further details.

6.2. Simulation 1

6.2.1. Design and procedure

The Ambiguity × Context × Age design of Experiment 1 was reproduced in this simulation, where age was simulated with the two values of the speed parameter, with $\alpha = 0.005$ for the slow model and .20 for the fast model. Each of the 16 sentence fragments was tested once in each combination of ambiguity and context, resulting in 64 "trials" at each level of speed. For each trial, the model was presented with stimuli, and the dependent variable was the time for the *us* node to accrue activation greater than 0 and begin firing. The condition means were analyzed using comparable tests to those used in Experiment 1, except that all model analyses were conducted with stimulus items as the random factor, because the simulation represents only one "participant."

Trials proceeded in three stages, as indicated in Fig. 5. At the first stage, beginning with the first time sample, a context word was presented, such as *warehouse* or *corporation.* If the trial represented an ambiguous condition, the node corresponding to the unambiguous syntactic constraint was given an input activation of 0, so that no syntactic constraint was present. For an unambiguous trial, the *could* node was given an input activation of 1, so that this began influencing the interpretation nodes for the ambiguous word. Activation of these nodes was allowed to accrue for 20 time samples before new input was presented in the next stage. The choice of 20 samples corresponds to having a short time to recognize and process the context word before the next word in the sentence is heard.

At Sample 21, the second stage began, with the ambiguous word being presented. The two word-interpretation nodes were given input according to their frequency biases, and the two contextual nodes were given input according to the offline sentence completion norms as described previously. The two context nodes began competing, with their activation being a function of the sentence completion values. The context competition was designed to begin at this stage rather than Stage 1 to reflect the fact that contexts such as *warehouse* and *corporation* are not inherently incompatible; it is only in conjunction with the presence of *fires* that they have different effects. In addition, the two alternative lexical ambiguity interpretation nodes began to compete at this stage, with their activity a function of (a) the relative frequency of the alternative meanings, (b) the contribution from the context nodes, and (c) any contribution from the syntactic constraint. Activation of these nodes was allowed to accrue for 20 more samples before new input was presented.

Finally, at Sample 41 the third stage began by presenting the disambiguating word *us.* Its activation was influenced by excitatory and inhibitory connections from the nodes that were activated in Step 2. The more strongly activated a node, the stronger the excitatory or inhibitory input, so if the verb interpretation of the ambiguity were winning, it would lend activation to the word *us,* speeding its accrual of activation. If the noun interpretation of the ambiguity were winning, however, it would inhibit the *us* node, slowing its accrual of activation. We assume that participants within Experiment 1 must have activated the representation of *us* to some threshold before naming it aloud, so the model's activation of the *us* node provides a mechanism for simulating comprehenders' performance in the naming task. Thus the number of time samples until the *us* node began firing was the dependent variable in the simulations.

The *us* node was given an initial bias of –1.0, and like all units in the network began firing when its output potential reached a positive value. The context nodes were each given negative biases of –0.5, as were the interpretation nodes. At Sample 41, when the *us* node was activated, it was given an input of 2.1. This value was chosen because its bias was –1, and the weights from the interpretation nodes were +/–1.0, so the *us* node would eventually begin firing even in the presence of unhelpful contexts. For example, if neither interpretation node were firing (i.e., they were still resolving their competition), then the input to the *us* node was 1.1; if the helpful (verb-supporting) interpretation node was firing, its input was 2.1, and if the unhelpful (noun-supporting) interpretation node was firing, its input was 0.1. The magnitude of these inputs, coupled with the global speed parameter dictated how rapidly the *us* node began firing.

6.2.2. Results and discussion

The number of time samples required for the *us* node to reach a value greater than 0 and begin firing is presented in Fig. 6. An examination of the fast (i.e., "young") model revealed a significant Ambiguity × Context interaction, $F(1, 30) = 18.9$, $MSE = 13.06$, $p < .001$. By contrast, the slow model, which simulated the older adults, produced only a main effect of ambiguity,

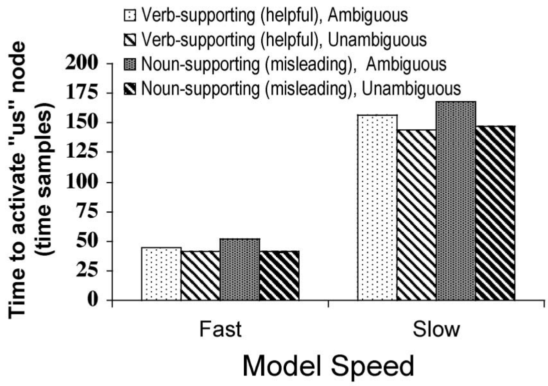

Fig. 6. Time to reach activation threshold for the visual target *us* for two speed parameters as a function of ambiguity and context, Simulation 1.

$F(1, 30) = 20.3$, $MSE = 216.8$, $p < .001$. The effect of context was only marginally reliable, $F(1, 30) = 3.2$, $p = .082$, and there was no Ambiguity × Context interaction, $F(1, 30) = 1.1$.

The model's results closely replicated the naming times of Experiment 1, in that naming performance of the young adults, such as that of the fast model, yielded the same Ambiguity × Context interaction, whereas the older adults' naming times yielded a main effect of ambiguity, but no interaction, as was found for the slow model.

These results stem from the biases in the language input and from the dynamics of the model. First, consider why there is a much larger effect of context in the fast model than in the slow one. Context influences the time to fire the "us" node through firing of the interpretation nodes (e.g., the noun or verb interpretation of the ambiguous word). The frequency biases on these nodes generally favor the noun interpretation, but a verb-supporting context may eventually overcome this bias. In verb-supporting contexts, the verb-supporting context node generally receives greater activation than its competitor (the reverse is true in noun-supporting context), but it takes time for the two nodes to resolve their competition. In the fast model, this competition is more likely to be resolved within the time between presentation of words (20 time samples), and hence a winner is declared by the time the *us* node is presented. In the slow model, it is more often the case that the context nodes are still resolving their competition; no winner has been declared, and hence they are not exerting any force on the interpretation nodes. Thus there is less of an effect of context in the slow model. There is, however, an effect of ambiguity in the slow model, for two reasons. First, the weight from the syntactic constraint node to the interpretation nodes was greater than the weights from the context nodes, reflecting the fact that the syntactic context from *could* is stronger than the semantic contexts such as *warehouse* and *corporation.* Second, the syntactic constraint from *could* begins in the first stage, whereas the effect of semantic context influences the ambiguous word only in the second stage. This situation reflects the fact that the syntactic information is constraining independent of upcoming material, in that *could* demands that the next word be a verb, but the semantic constraint from *warehouse* or *corporation* is really effective only in conjunction with the ambiguous word. In sum, the syntactic constraint can force the winner of the competition between the interpretation nodes much faster than the semantic context nodes can.

The preceding analysis suggests that processing speed, the strength of the context, and the time available to resolve competitions in the model are all crucial factors in context use. This pattern is consistent with results from Experiments 1 to 3, in which older participants were able to use context in compatibility judgments and sentence completions but not in cross-modal naming. To more fully explore the interaction of speed and time to resolve competition, we conducted a second simulation specifically varying these two factors.

6.3. Simulation 2

In contrast to the cross-modal naming task, the compatibility judgment task in Experiments 1 and 2 and the sentence completion task in Experiment 3 produced good use of context by older adults, which was attributed to additional time in these tasks to process the context and integrate it with the ambiguous word. Simulation 2 explores this claim, that as available time to integrate context and ambiguity increases, the advantage of fast models over slow models will decrease so that all models will make good use of context in the absence of time pressure.

6.3.1. Method

The time to process context was manipulated by varying the number of samples between when the ambiguity is presented at time Sample 20 and when the disambiguating *us* node is presented. Rather than choosing one new value of ambiguity–disambiguation lag, Simulation 2 explored 25 values of lag, ranging from 20 to 140 samples, in five-sample increments. We also examined 30 values of model speed by varying α from 0.001 to 0.2, exponentially. With a resulting space of 750 combinations of speed and lag, we can therefore view the conjoint effects of processing speed and stimulus presentation rate over a much larger range of conditions than is feasible in experiments with human participants.

We ran the simulation in the ambiguous conditions, manipulating noun- versus verb-supporting context at each of the 750 combinations of lag and speed. There were 32 trials at each lag–speed combination (from the 16 noun- and verb-supporting contexts). The times until activation of the *us* node were recorded as in Simulation 1.

6.3.2. Results and discussion

The dependent variable, *us* node activation time, was the same as in Simulation 1, but to aid in a graphical display of the results, we calculated a difference score between results from the helpful verb-supporting context versus the misleading noun-supporting context. Formally, we recorded the mean time until activation of the *us* node in the noun-supporting context fragments minus the mean time for the verb-supporting context, all divided by the mean time for the noun-supporting context. This calculation resulted in values reflecting proportional improvement in activation time due to helpful context, which are shown in Fig. 7; larger values represent larger improvements in activation time. The approximate locations of conditions corresponding to Simulation 1 are indicated with arrows in the figure. The graph shows that at short lags, including but not limited to the lag parameter used in Simulation 1, the effect of context is dramatically larger for the fast model than the slow model. Thus these data show that the results of Simulation 1 were not an accident, in that the close simulation of the young and old data did not depend on only one idiosyncratic lag parameter and one speed parameter for each age.

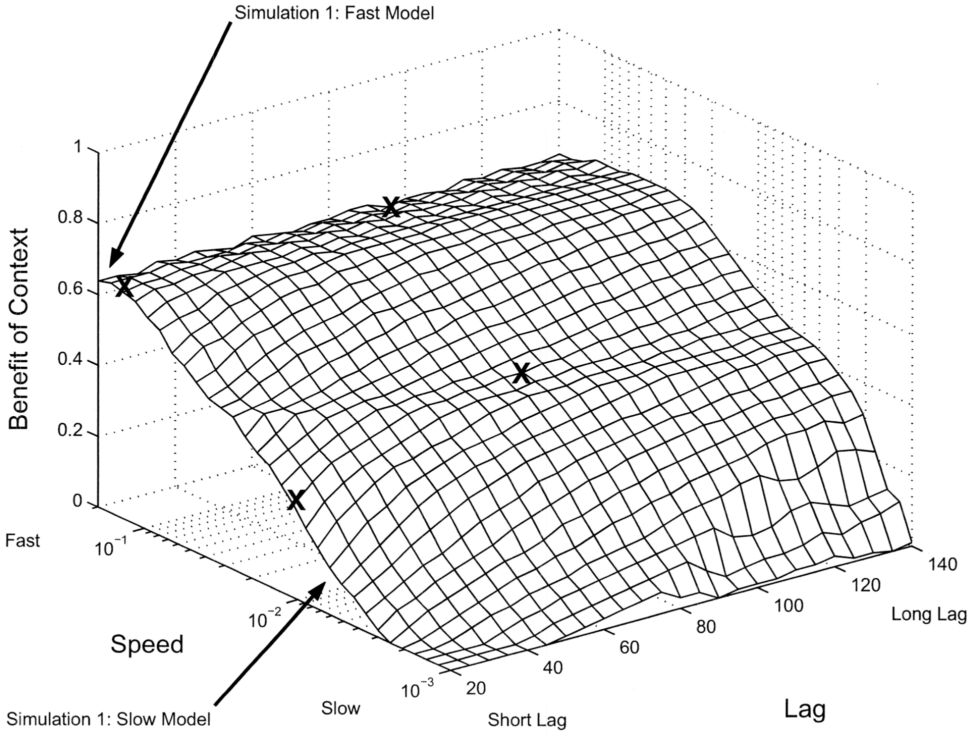

Fig. 7. Benefit of helpful context at 750 combinations of processing speed and ambiguity–disambiguation lag, Simulation 2. Arrows indicate the location of values tested in Simulation 1. *X*s indicate values chosen for additional factorial analysis in Simulation 2.

Fig. 7 also shows that at longer lags, the effect of context becomes more robust for networks of all speeds. This result relates well to the compatibility judgments and sentence completion data from the experiments, where older adults did show good use of context. In the model, the context nodes have more time to resolve their competition at larger values of lag, and hence the slow models shows a much larger effect of context than at shorter lags.

To demonstrate these points more concretely, we chose a pair of speeds and lags for a factorial analysis. We contrasted model speeds of .01 and .198 and lags of 20 and 80; the four combinations of these values are shown with *X*s in Fig. 7. We examined the effect of these factors on *us* node activation time in an ANOVA crossing speed, lag, and context, with context a between-item factor and speed and lag within-items factors. As is clear from the difference scores in the figure, there was a reliable interaction of all three factors at these chosen values, $F(1, 30) = 9.80$, $MSE = 907.7745$, $p < .01$, such that at the short lag (20 samples), context was much more effective for the fast model than for the slow model, but at the longer lag (80 samples), both the fast and slow models were aided by helpful context. No particular significance should be attached to the choice of these speed and lag values or size of the interaction effect obtained here; the shape of the space in Fig. 7 indicates that we could have obtained a similar interaction with many other values of lag and speed, and we also could have chosen values with too small a range of speed or lag to yield a reliable interaction. This analysis is merely designed to reinforce what Fig. 7 shows graphically, that the integration of contextual information and the ambiguous word takes time, and ability to use such information depends both on the speed at which such information can be integrated and the amount of time available to do this integration.

7. General discussion

This research used both empirical studies and computational modeling to investigate effects of aging on the use of context during language comprehension. Experiments 1 and 2 showed that under the time constraints imposed by the cross-modal naming task and stimuli in which a single context word immediately preceded an ambiguous one, younger adults, but not older adults, were able to use semantic context information to resolve an ambiguity. Experiment 3 showed that both older and younger adults had comparable knowledge about contexts. We interpreted this pattern across experiments as suggesting that the extent to which a comprehender can use contextual information during language comprehension depends on the strength of the context, the time available to process the context, and the processing speed or efficiency of the comprehender. We explored these factors in two computational simulations of ambiguity resolution that successfully simulated the pattern of empirical results and explored the complex interactions of these factors over a large space of conditions.

We have suggested that the experimental results are consistent with a slowing account of aging and language processing. The simulations support this view, in that the manipulation of a single speed parameter resulted in a reduction in context use and thus a relatively greater reliance on frequency in ambiguity resolution in the slower models compared to the faster ones. Both the empirical data and the simulations are thus an instantiation of Myerson et al.'s (1990) claim that cognitive slowing, even if it is a general phenomenon, will not affect all behaviors equally; more complex processes (context use, in this case) will be impaired by slowing to a greater degree than simpler processes (frequency use). These results are also broadly consistent with studies of individual differences in comprehension efficiency in young adults and children, where less skilled comprehenders (assessed by performance on comprehension or verbal working memory tests or both) show limited or slower use of contextual information relative to more efficient comprehenders (Gernsbacher, Varner, & Faust, 1990; Merrill, Sperber, & McCauley, 1981; Pearlmutter & MacDonald, 1995; Van Petten, Weckerly, McIsaac, & Kutas, 1997).

We next turn our attention to cognitive aging and address two issues. First, we consider how these results fit in the existing literature on aging and context use during language comprehension. Second, we consider the theoretical interpretation of these results and the extent to which alternative accounts of cognitive aging could also capture these results.

7.1. Context, time, and aging

As noted in the introduction, a number of studies have found that older adults exhibit poorer language comprehension abilities compared to younger adults. A few studies in the literature, however, have failed to find age differences in context use or other language comprehension abilities (e.g., Burke & Harrold, 1988; Hopkins et al. 1995; Light, Valencia-Laver, & Zavis, 1991). We have argued that context strength, time to process context, and processing efficiency or speed are all important factors determining whether a comprehender will make good use of contextual information during language comprehension. Given this claim, a logical hypothesis is that studies that have failed to find effects of aging on language comprehension differ from those that do find age effects in some of the factors modulating context use, particularly context strength or the time available to process the context. Studies published to date vary in many dimensions, making precise comparisons difficult, but examination of stimulus items in appendixes or examples in tables suggests that at least some of the studies reporting good context use in older adults tend to allow greater time to process the context, either by early appearance of contextual information relative to some critical word or by using a measure of comprehension taken some time after the context and critical material had been integrated. For example, participants in Light et al.'s study made judgments about context-relevant words that appeared after a complete sentence had been read. This task had similar timing parameters to the compatibility judgment task in these experiments, for which older adults did show good context use, as did the older adults in Light et al.'s study. Given these timing parameters, good use of context in Light et al.'s study is entirely consistent with these results. Similarly, Hopkins et al. (1995) used materials and a procedure that might be conducive to boosting context use in older adults. They examined younger and older adults' context use in interpretation of ambiguous words using a somewhat similar method to the one used here, in that the ambiguous word was always the last word of a sentence, and the dependent measure was naming time to a visually presented word. However, Hopkins et al.'s contexts, which are fully reported in their article, appear to be generally stronger than the ones used here. Over half of their contexts provided strong syntactic information to force one interpretation of the ambiguous word (e.g., *saw a duck* vs. *had to duck*); recall that Experiment 1 here showed that older adults did make good use of syntactic context to resolve ambiguities. Second, Hopkins et al. used a visual presentation of the sentence rather than auditory presentation as was done here, and they adjusted the rate at which the sentence words were presented for each participant on the basis of performance on a pretest. Presentation rates for the older participants were reliably slower than for younger participants. These slower presentation rates provide additional time to process the context and integrate it with the ambiguous word, which should ameliorate any effects of cognitive slowing in older adults. Thus, whereas the Hopkins et al. results and these results may initially appear to conflict, in fact the pattern of findings across the two studies are quite consistent when the stimulus and timing parameters of the two studies are considered. These points are clearly not criticisms of Hopkins et al.; rather they illustrate a continuum of outcomes that can be obtained with variations in context strength and processing time.

These comparisons across studies suggest that the manipulation of available context and ambiguity processing time within the sentence is an important avenue for additional research. Indeed, studies that manipulate the lag between the context and ambiguity, or between the ambiguity and disambiguation, or both, could avoid one limitation of our own studies, in that these time intervals were confounded with task (target naming vs. compatibility judgment vs. sentence completion). In practice, however, this goal is quite difficult to realize. Specifically for the noun–verb lexical category ambiguities investigated here, it is virtually impossible to insert one or more words in between the ambiguous word and the disambiguating visual target, as in … *the warehouse fires* ____ *us* and still have a grammatical sentence. An alternative to creating a delay with additional lexical material is to simply increase the ISI between the offset of the ambiguous word and the appearance of the visual target (there was a 0 msec ISI in these experiments, in that the visual target appeared with the acoustic offset of the ambiguous word). This blank interval might allow additional time to process the ambiguity and context, but it could also reduce the extent to which the visual target is integrated with the auditory sentence fragment so that responses to the visual target are no longer informative about what interpretation is adopted.

Beyond the particular type of ambiguity used here, manipulating the ambiguity–context or ambiguity–disambiguation lag is complicated by the complexity of the notion of "context" in ambiguity resolution. It is important to consider how these issues affect interpretation of aging and language processing results. First, some contexts, such as the syntactic disambiguating context used in Experiment 1, have their effect fairly independently of the actual ambiguous word. For example, following *warehouse could,* the next word is very strongly constrained to be a verb, independent of whether this word turns out to be *fire, guard, precipitate,* or any other word with a possible verb interpretation. For more semantic or pragmatically based contexts, such as were used in the ambiguous conditions of these studies and in most studies of ambiguity resolution in the literature, the context can have its full effect only in conjunction with the actual ambiguous word. The fact that many context effects are dependent on the appearance of the ambiguous word means that the raw number of words between key contextual elements and the ambiguous word captures only one sense of "time to process context"; another aspect is the amount of integration that must be delayed until the appearance of the ambiguous word itself.

7.1.1. Alternative accounts of processing efficiency

We have described adults' reduced abilities to use context rapidly during language comprehension as owing to slowed processing, and we have modeled these changes in cognitive aging through manipulation of a speed parameter in the models, but it is important not to overinterpret the model or the account. Current theorizing in cognitive aging offers a wide variety of accounts for performance declines, including slowing (Salthouse, 1996), inhibition deficits (Hasher & Zacks, 1988), or other declines in attentional modulation (Balota et al., 2001; Braver et al., 2001), reductions in working-memory capacity (Carpenter & Just, 1992; van der Linden et al., 1999), transmission deficits (MacKay & Burke, 1990), and perceptual deficits that increase noise in the acoustic and visual signal (Schneider et al., 2002). Although researchers are actively working to better specify and distinguish these alternative accounts, at this level of theorizing, they are to some extent all instantiations of the same basic idea that older adults' cognitive processing is less efficient than that of younger adults. Thus although our computational model has a speed parameter, we do not assume that there is literally a speed parameter in the brain, and of course this slowing, or more neutrally, this decline in efficiency, must itself have a cause. For example, declines in processing speed or efficiency, as modeled in our network, could be caused by additional noise in the speech signal (Schneider et al., 2002) or poorer attentional modulation (Braver et al., 2001), either of which could plausibly slow down processing. Thus, although we are in principle highly supportive of the goal of distinguishing between alternative theoretical accounts, we also see a place for more cautious reflection about the highly overlapping and often underspecified nature of constructs such as speed, transmission efficiency, inhibition efficiency, and others. On that view, whereas our data and models are certainly consistent with a slowing account of cognitive aging, neither our results nor any single result in the available literature truly support a single approach to the complete exclusion of alternative views.

What then is the value of empirical and computational investigations such as those presented here if the state of theorizing admits so many different instantiations of processing efficiency? We see several benefits to our approach. First, there is value in demonstrating that a single parameter, affecting all nodes in the network, can affect different behaviors to different degrees and capture substantial changes in language comprehension in aging. This demonstration is important independent of whether one conceptualizes the parameter as processing speed, or transmission efficiency, amount of noise in the signal, or other potential contributors to processing efficiency. Second, this work makes strides toward rationalizing the conflicting findings in the literature concerning use of context during language comprehension by young and old adults. We have emphasized that all contexts are not created equal, not only in their strength (a point that is well appreciated in the literature) but also in their time course relative to an ambiguity or other target word or region of a sentence. A related issue concerns potential ambiguity and shades of meaning in contexts themselves, as in the *gym … boxer* and *pet store … boxer* examples in the introduction. Such cases violate a frequently held assumption about language comprehension, that prior information (the context) constrains interpretation of later information (the ambiguity) but not the other way around. In the *boxer* example, and in many other occurrences in language, the ambiguous word and the prior context mutually constrain each other to yield an interpretation that maximally satisfies the available interpretations across the various words in the sentence. This notion of language comprehension as a massive constraint–satisfaction process seems at present to have more currency in studies of young adults than in cognitive aging. Our suggestion here is that further attention to the constraints provided in the linguistic signal, and the time course over which this information is computed, will be informative in better characterizing the changes in language comprehension that accompany cognitive aging.

Acknowledgments

Portions of these studies were presented at the CUNY Conference on Human Sentence Processing and the Cognitive Aging Conference and were supported by NIH Grants R01–AG11773 and P50–MH64445.

References

Almor, A., Kempler, D., MacDonald, M. C., Andersen, E. S., & Tyler, L. K. (1999). Why do Alzheimer patients have difficulty with pronouns? Working memory, semantics, and reference in comprehension and production in Alzheimer's disease. *Brain and Language, 67,* 202–227.

Amari, S., & Arbib, M. A. (1977). Competition and cooperation in neural nets. In J. Metzler (Ed.), *Systems neuroscience* (pp. 119–165). San Diego, CA: Academic.

Arbib, M. A. (1989). *The metaphorical brain: Neural networks and beyond.* New York: Wiley.

Balota, D. A., Cortese, M. J., & Wenke, D. (2001). Ambiguity resolution as a function of reading skill, age, dementia, and schizophrenia: The role of attentional control. In D. Gorfein (Ed.), *On the consequences of meaning selection* (pp. 87–102). Hove, England: Psychology Press.

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., et al. (2001). Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General, 130,* 746–763.

Burke, D. M., & Harrold, R. M. (1988). Automatic and effortful semantic processes in old age: Experimental and naturalistic approaches. In L. L. Light & D. M. Burke (Eds.), *Language, Memory, and Aging* (pp. 100–116). New York: Cambridge University Press.

Cohen, G. (1981). Inferential reasoning in old age. *Cognition, 9,* 59–72.

Cooper, W. E., & Paccia-Cooper, J. (1980). *Syntax and speech.* Cambridge, MA: Harvard University Press.

Cottrell, G. W. (1989). *A connectionist approach to word sense disambiguation.* San Mateo, CA: Kaufmann.

Francis, W. N., & Kucera, H. (1982). *Frequency analysis of English usage: Lexicon and grammar.* Boston, MA: Houghton Mifflin.

Gernsbacher, M. A., Varner, K. R., & Faust, M. E. (1990). Investigating differences in general comprehension skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 430–445.

Hale, S., & Myerson, J. (1995). Fifty years older, fifty percent slower? Meta-analytic regression models and semantic context effects. *Aging and Cognition, 2,* 132–145.

Hasher, L. & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic.

Hopkins, K. A., Kellas, G., & Paul, S. T. (1995). Scope of word meaning activation during sentence processing by young and older adults. *Experimental Aging Research, 21,* 123–142.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 98,* 122–147.

Kawamoto, A. (1993). Nonlinear dynamics in the resolution of lexical ambiguity: A parallel distributed processing account. *Journal of Memory and Language, 32,* 474–516.

Kemper, S. (1986). Imitation of complex syntactic constructions by elderly adults. *Applied Psycholinguistics, 7,* 277–287.

Kemper, S. (1987). Life-span changes in syntactic complexity. *Journal of Gerontology, 42,* 323–328.

Kempler, D., Almor, A., Tyler, L. K., Andersen, E. S., & MacDonald, M. C. (1998). Sentence comprehension deficits in Alzheimer's disease: A comparison of off-line vs. on-line sentence processing. *Brain and Language, 64,* 297–316.

Kwong See, S. T., & Ryan, E. B. (1995). Cognitive mediation of adult age differences in language performance. *Psychology and Aging, 10,* 458–468.

Kynette, D., & Kemper, S. (1986). Aging and the loss of grammatical forms: A cross sectional study of language performance. *Language and Communication, 6,* 43–49.

Leonard, C. L., Waters, G. S., & Caplan, D. (1997). The influence of contextual information on the resolution of ambiguous pronouns by younger and older adults. *Applied Psycholinguistics, 1,* 293–317.

Light, L. L., & Capps, J. L. (1986). Comprehension of pronouns in younger and older adults. *Developmental Psychology, 22,* 580–585.

Light, L. L., Valencia-Laver, D., & Zavis, D. (1991). Instantiation of general terms in young and older adults. *Psychology and Aging, 6,* 337–351.

Lindfield, K. C., & Wingfield, A. (1999). An experimental and computational analysis of age differences in the recognition of fragmented pictures: Inhibitory connections versus speed of processing. *Experimental Aging Research, 25,* 223–242.

MacDonald, M. C. (1993). The interaction of lexical and syntactic ambiguity. *Journal of Memory and Language, 32,* 692–715.

MacDonald, M. C., Pearlmutter, N. J., & Seidenberg, M. S. (1994). The lexical nature of syntactic ambiguity resolution. *Psychological Review, 101,* 676–703.

MacKay, D. G., & Burke, D. M. (1990). Cognition and aging: A theory of new learning and the use of old connections. In T. M. Hess, (Ed.), *Aging and cognition: Knowledge organization and utilization* (pp. 213–263). Amsterdam: North-Holland.

McRae K., Spivey-Knowlton, M. J., & Tanenhaus, M. K. (1998). Modeling the influence of thematic fit (and other constraints) in on-line sentence comprehension. *Journal of Memory and Language, 38,* 283–312.

Merrill, E. C., Sperber, R. D., & McCauley, C. (1981). Differences in semantic encoding as a function of reading comprehension skill. *Memory and Cognition, 9,* 618–624.

Morrow, D. G., Altieri, P., & Leirer, V. (1992). Aging, narrative organization, presentation mode, and referent choice strategies. *Experimental Aging Research, 18,* 75–84.

Myerson, J., Ferraro, F. R., Hale, S., & Lima, S. D. (1992). General slowing in semantic priming and word recognition. *Psychology and Aging, 7,* 257–270.

Myerson, J., Hale, S., Wagstaff, D., Poon, L. W., & Smith, G. (1990). The information loss model: A mathematical theory of age related cognitive slowing. *Psychological Review, 97,* 475–487.

Pearlmutter, N. J. & MacDonald, M. C. (1995). Individual differences and probabilistic constraints in syntactic ambiguity resolution. *Journal of Memory and Language, 34,* 521–542.

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *Journal of the Acoustical Society of America, 97,* 593–608.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 10,* 403–428.

Schneider, B. A., Daneman, M., & Pichora-Fuller, K. M. (2002). Listening in aging adults: From discourse comprehension to psychoacoustics. *Canadian Journal of Experimental Psychology, 56,* 139–152.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review, 96,* 523–568.

Speranza, F., Daneman, M., & Schneider, B. A. (2000). How aging affects the reading of words in noisy backgrounds. *Psychology and Aging, 15,* 253–258.

Stine, E. L., & Hindman, J. (1994). Age differences in reading time allocation for propositionally dense sentences. *Aging, Neuropsychology, and Cognition, 1,* 2–16.

Tanenhaus, M. K., Spivey-Knowlton, M. J., & Hanna, J. E. (2000). Modeling thematic and discourse context effects with a multiple constraints approach: Implications for the architecture of the language comprehension system. In M. W. Crocker & M. Pickering (Eds.), *Architectures and mechanisms for language processing* (pp. 90–118). New York: Cambridge University Press.

Tun, P. A., & Wingfield, A. (1997). Language and communication: Fundamentals of speech communication and language processing in old age. In A. D. Fisk & W. A. Rogers (Eds.), *Handbook of human factors and the older adult* (pp. 125–149). San Diego, CA: Academic.

Tun, P. A., & Wingfield, A. (1999). One voice too many: Adult age differences in language processing with different types of distracting sounds. *Journals of Gerontology: Series B: Psychological Sciences and Social Sciences, 54,* P317–P327.

Tun, P. A., Wingfield, A., Stine, E. A. L., & Mecsas, C. (1992). Rapid speech processing and divided attention: Processing rate versus processing resources as an explanation of age effects. *Psychology and Aging, 7,* 546–550.

Tyler, L. K., & Marslen-Wilson, W. D. (1977). The on-line effects of semantic context on syntactic processing. *Journal of Verbal Learning and Verbal Behavior, 16,* 683–692.

Van der Linden, M., Hupet, M., & Feyereisen, P. (1999). Cognitive mediators of age-related differences in language comprehension and verbal memory performance. *Aging, Neuropsychology, and Cognition, 6,* 32–55.

Van Petten, C., Weckerly, J., McIsaac, H. K., & Kutas, M. (1997). Working memory capacity dissociates lexical and sentential context effects. *Psychological Science, 8,* 238–242.

Wingfield, A. (2000). Speech perception and the comprehension of spoken language in adult aging. In D. C. Park & N. Schwarz (Eds.), *Cognitive aging: A primer* (pp. 175–195). Philadelphia: Psychology Press/Taylor & Francis.

Wingfield, A., & Stine-Morrow, E. L. (2000). Language and speech. In F. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (pp. 359–416). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Wingfield, A., Tun, P. A., Koh, C. K., & Rosen, M. J. (1999). Regaining lost time: Adult aging and the effect of time restoration on recall of time-compressed speech. *Psychology and Aging, 14,* 380–389.

Zacks, R. T., & Hasher, L. (1988). Capacity theory and the processing of inferences. In L. L. Light & D. M. Burke (Eds.), *Language, Memory, and Aging* (pp. 154–170). New York: Cambridge University Press.
Zurif, E., Swinney, D., Prather, P., Wingfield, A., & Brownell, H. (1995). The allocation of memory resources during sentence comprehension: Evidence from the elderly. *Journal of Psycholinguistic Research, 24,* 165–182.

Appendix A. Untransformed RTs in Msec and Standard Errors, Experiment 1

	Context			
	Verb-Supporting (Helpful)		Noun-Supporting (Unhelpful)	
	Ambiguous	Unambiguous	Ambiguous	Unambiguous
Young adults	632 (35)	613 (33)	685 (38)	582 (25)
Older adults	1480 (105)	1298 (90)	1555 (134)	1365 (127)

Note. RTs = response times. Standard errors given in parentheses.

Appendix B. Untransformed RTs and Standard Errors, Experiment 2

	Context		
	Verb-Supporting (Unhelpful)	Noun-Supporting (Helpful)	Adjective (Unambiguous)
Young Adults	708 (37)	668 (30)	661 (30)
Older Adults	1196 (95)	1197 (87)	1174 (88)

Note. RTs = response times. Standard errors given in parentheses.

Appendix C. Computational Modeling Details

The model was constructed using software developed by the third author. In the network coding, each unit has an *activation,* which can be thought of as a membrane potential in a biological neuron. Once this activation, or membrane potential, crosses a given threshold, the unit *fires.* The firing of a unit is a means of communicating with other units.

The activation level of each unit is modeled as a *leaky integrator.* This means that the unit's activation approaches a target value at a rate proportional to the difference between its instantaneous activation and its target value. Precisely, this is expressed by the formula $\alpha \frac{\partial o}{\partial t} = -o + x_i + h_i$. Here, o is the activation of the unit, t is a unit of time, x is the input to the unit, and h is a resting potential or *bias* on the unit, and α is the speed parameter. The activation level o will eventually settle to the sum $x_i + h_i$. The speed at which the activation level approaches this sum is determined by the speed parameter. The strength of the input to a unit determines how fast its activation rises, and this in turn determines how soon it begins firing.

The model has a number of pairs of units that operate in a winner-take-all fashion; that is, only one unit can ultimately be firing. To implement the winner-take-all scheme, we used a competitive winner-take-all subnetwork as proposed by Amari and Arbib (1977). In this scheme, each unit receives excitatory input from itself according to a weight w_1; that is, the more strongly a unit is firing, the more likely it is to continue firing. In addition, there is a single unit that is activated by all units in the network; its firing is proportional to the activations of all competitors. This unit in essence behaves as a governor for the set of competing units; its firing inhibits all units equally, according to weighted inhibitory connections (w_2). The effect of the governor unit is to "raise the bar" for how strongly a unit needs to be firing to continue firing. The closer the two competing units are in their activation strengths, the longer it takes the governor unit to fully inhibit the less active unit. Arbib (1989) provides a mathematical derivation and proof showing that with appropriate choices of interconnection weights w_1 and w_2, each competition subnetwork will activate only the most strongly activated unit of the set and, further, that the final output will be asymptotically stable.