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The Effects of Context on Processing Words During Sentence Reading Among Adults Varying in Age and Literacy Skill

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The facilitation of word processing by sentence context reflects the interaction between the build-up of message-level semantics and lexical processing. Yet, little is known about how this effect varies through adulthood as a function of reading skill. In this study, Participants 18–64 years old with a range of literacy competence read simple sentences as their eye movements were monitored. We manipulated the predictability of a sentence-final target word, operationalized as cloze probability. First fixation durations showed an interaction between age and literacy skill, decreasing with age among more skilled readers but increasing among less skilled readers. This pattern suggests that age-related slowing may impact reading when not buffered by skill, but with continued practice, automatization of reading can continue to develop in adulthood. In absolute terms, readers were sensitive to predictability, regardless of age or literacy, in both early and later measures. Older readers showed differential contextual sensitivity in regression patterns, effects not moderated by literacy skill. Finally, comprehension performance increased with age and literacy skill, but performance among less skilled readers was especially reduced when predictability was low, suggesting that low-literacy adults (regardless of age) struggle when creating mental representations under weaker semantic constraints. Collectively, these findings suggest that aging readers (regardless of reading skill) are more sensitive to context for meaning-integration processes; that less skilled adult readers (regardless of age) depend more on a constrained semantic representation for comprehension; and that the capacity for literacy engagement enables continued development of efficient lexical processing in adult reading development.

Keywords: language, sentence processing, midlife, comprehension, context

A substantial body of work has examined how the impact of contextual constraints on the processing of individual words varies with age through adulthood (cf. Wingfield & Stine-Morrow, 2000, for a review). However, much of what is known about adult development in cognition, language processes, and reading is based on extreme-group comparisons between younger and older adults, such that very little is known about development into midlife—a period in the life span at which the effects of knowledge and experience are in full bloom, and the effects of cognitive slowing and other senescence-related processing declines are not fully manifest (Salthouse, 2012). Midlife is also a time when literacy demands from work and life management are most acute. Furthermore, most research investigating this issue, as well as adult-developmental research on language more generally, has relied on samples of adults with well-developed literacy skills, even while a growing body of research suggests that age effects in language processing may depend on verbal ability and print exposure (e.g., Chin et al., 2015; Meyer & Rice, 1989; Payne, Gao, Noh, Anderson, & Stine-Morrow, 2012; Payne, Grison, Gao, Christianson, Morrow, & Stine-Morrow, 2014; Stine-Morrow, Miller, Gagne, & Hertzog, 2008). As a result, little is known about reading processes and text–word interactions among adults with lower levels of literacy skill. Thus, this research has neglected the

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substantial segment of the adult population that has only acquired the most rudimentary skills in decoding print and using text to gain information or as a stimulus for thought (National Research Council, 2012; OECD, 2013). Important to note, well-developed literacy has been shown to have benefits for cognition and physical health (Manly, Byrd, Touradji, Sanchez, & Stern, 2004; Manly, Schupf, Tang, & Stern, 2005), so that a full understanding of the variation in adult reading skills could contribute to public health policy.

Our goal in this study, therefore, was to examine language comprehension among adults ranging in age from young to midlife who also varied widely in literacy skill. We specifically focused on the use of sentence context to build up a message-level representation so as to ease word-level processing demands, given the known roles of both lexical processing efficiency and language experience and knowledge in such effects.

Contextual Facilitation in Language Processing

One of the most well-replicated findings in reading is facilitated processing for words that are predictable within the larger sentence or discourse context (e.g., Duffy, Morris, & Rayner, 1988; Rayner & Well, 1996). Many studies have examined the use of context in reading by manipulating semantic constraints of the sentence prior to a target word. In this research, word predictability is typically quantified in terms of cloze probability, the likelihood of producing a particular word as the completion of a particular sentence frame. For example, most readers will complete the sentence frame, "As soon as they reached the sand, he stopped to take off his . . . ," with "shoes" rather than "watch," although the latter is a plausible continuation. Contextual facilitation (e.g., faster processing of shoes relative to watch) has been observed in studies using a variety of measures, including reaction time (RT) for lexical decision and naming tasks (Stanovich & West, 1979), reading times (Ehrlich & Rayner, 1981; Rayner et al., 2001, 2006), speech recognition (Stine & Wingfield, 1994), and electrophysiological measures during reading (Kutas & Federmeier, 2011).

Early accounts of contextual facilitation focused on the use of context to reduce the threshold for the amount of visual information needed for word recognition (Ehrlich & Rayner, 1981; Balota, Pollatsek, & Rayner, 1985). More recent theories assume that context evokes a spread of activation that primes semantic features of the constrained word (Kintsch, 1988). At the same time, some models conceptualize activation of features as a passive process that facilitates integration, whereas others evoke a more proactive process of prediction (see van Petten & Luka, 2012, and Kuperberg & Jaeger, 2016, for reviews). Eye-tracking provides a temporally sensitive method for examining the extent to which contextual constraint facilitates reading. A predictive sentence context can decrease gaze durations on a target by 20–25 ms, increase the probability of skipping, and decrease spillover effects and the probability of regressions, suggesting that contextual constraint impacts both early word-recognition processes and postaccess integration processes (Ashby, Rayner, & Clifton, 2005; Balota et al., 1985; Ehrlich & Rayner, 1981; Kliegl et al., 2004). The effects of context have also been revealed using event-related potentials (ERPs; i.e., electrical brain activity time-locked to an event). ERPs to meaningful stimuli, including words, show a characteristic negative deflection that peaks at approximately 400 ms after stimulus onset (known as the N400) and that has been linked to the access of semantic information from long-term memory (Federmeier & Laszlo, 2009). A large body of literature has shown that the amplitude of this N400 at central-parietal sites is graded with cloze probability, such that N400s are reduced for words that are more expected, given the preceding context, relative to words that are less expected (i.e., the "N400 effect;" Kutas & Federmeier, 2011; Federmeier, 2007; Federmeier, Wlotko, Ochoa-Dewald, & Kutas, 2007; Wlotko, Federmeier, & Kutas, 2012).

The effective use of context depends on the rapid construction of a representation of a text's meaning that is available at or before the fixation of the target word. Thus, ultimately, contextual facilitation emerges from a balance between, on the one hand, the efficiency of semantic and situation-model processes that activate meaning in advance of the apprehension of any given word and, on the other, word recognition and integration processes that are initiated when that word is encountered—both component skills for which there is considerable individual variation (e.g., Landi, 2010).

Age-Related Differences in Contextual Facilitation

Individuals differ in the degree to which they show context effects on word processing. Relative to their younger counterparts, older adults have been shown to take differential advantage of context during word recognition and lexical processing in both speech recognition (e.g., Stine & Wingfield, 1994; Lash, Rogers, Zoller, & Wingfield, 2013) and self-paced reading (Madden, 1988; Stine-Morrow et al., 2008), suggesting an age advantage in creating a message-level representation that can facilitate word recognition and integration. As noted above, however, little is known about contextual facilitation in midlife when knowledge and experience have been built up (relative to younger adults), but declines in fluid abilities and sensory loss are not yet manifest (Salthouse, 2012). The few studies that have been conducted on language processing with middle-aged adults and adults in the "young-old" range present a picture that is generally optimistic for language abilities in midlife. Age-related changes in naming are generally stable through midlife and only begin to decline in a significant way in older adult age ranges (e.g., beginning in the 6th decade; Connor et al., 2004; Ramsay et al., 1999). Whereas some studies on comprehension have suggested that change may be continuously graded through the life span (Ferstl, 2006; Miller, 2009; Payne et al., 2014), other data show exceptionally good comprehension and memory performance using offline measures among younger old adults—relative to both the young- and old-old (i.e., an inverted U pattern; Stine-Morrow et al., 2008).

Because age differences in contextual facilitation have been found to increase as sensory input is degraded, for example, with the addition of auditory or visual noise (Cohen & Faulkner, 1983; Madden, 1988; Speranza, Daneman, & Schneider, 2000), these age-related changes are often characterized in terms of compensatory top-down analysis. Such a shift toward more top-down processing with age may be attributable to two different factors. First, it may be that age-related sensory declines result in a decrease in the quality of bottom-up input. For example, older readers are less disrupted in reading when high spatial frequencies are filtered out (Jordan, McGowan, & Paterson, 2014), supporting the idea that they get less bottom-up information from the fine details of the printed word. There is evidence that such declines are observable by the age of 40 (Schneider & Pichora-Fuller, 2000). On the other hand, movement through adulthood affords the opportunity to acquire knowledge and experience, which can impact the moment-to-moment processes in text understanding (Payne et al., 2012, 2014). Thus, a top-down shift might emerge from habitual reliance on knowledge that may grow richer with age (Miller et al., 2004). This principle of top-down dominance seems to apply at higher levels of analysis as well. Older adults are more likely to rely on gist rather than hippocampally mediated recollection in episodic memory (Dennis, Kim, & Cabeza, 2008), and in discourse understanding, older adults tend to form a higher level gist representation, whereas the representation of individual ideas in text is more fragile (Stine-Morrow & Radvansky, in press). However, the pattern of increased context sensitivity with age is not always observed. Time-sensitive measures, such as ERPs and eye-tracking, have shown patterns different from those seen with end-state behavioral measures.

N400 effects of sentence context are typically reduced among older, relative to younger, adults (Wlotko, Lee, & Federmeier, 2010), whereas lexical effects remain relatively intact (Federmeier, van Petten, Schwartz, & Kutas, 2003). Such changes, at least in part, seem to reflect the use of different processing strategies with age, such that older adults are less likely to use context predictively (e.g., Federmeier et al., 2003; Wlotko et al., 2012). Little work has been done using ERPs to study language comprehension in middle-aged adults, although it is known that the N400 shows systematic increases in latency and reductions in effect amplitude across the adult life span (Kutas & Iragui, 1998), similar to changes that have been documented for other sensory and cognitive responses (e.g., Goodin, Squires, Henderson, & Starr, 1978; Picton et al., 1984; Polich, 1997). Again, therefore, middle age stands out as an especially important period to study to try to tease apart the impact of processing strategy, experience, and slowing on various aspects of language comprehension, especially across samples that vary in their language skills and knowledge.

Thus far, eye-tracking, which yields a set of measures that differentially reflect early and later stages of processing, has also not provided strong evidence about whether and how the use of context information changes with age. Rayner et al. (2006) reported strong and comparable effects of contextual constraint for younger and older readers in both early and later measures. Kliegl et al. (2004) also found that predictability increased reading efficiency for both younger and older adults, but in different ways, increasing the probability of skipping among the young, but reducing the probability of multiple fixations among the old. Thus, while behavioral data have generally shown increased contextual facilitation with age and electrophysiological data have shown the reverse, the status of this effect with eye-tracking is less clear.

Skill-Related Differences in Contextual Facilitation

Contextual facilitation also varies with word knowledge and overall reading skill. Studies with children who are still learning to read have demonstrated that less skilled readers rely more on contextual information for word identification than their skilled peers whose more automatized lexical processing allows them to rely more on lower level orthographic information (Stanovich, 1980). However, very few studies have examined skill differences in the use of context among adult readers. Lower skilled adult readers have less efficient decoding and word recognition skills and poorer listening comprehension skills than higher-skilled adult readers (Bell & Perfetti, 1994). To our knowledge, there is only a single behavioral study that has examined the effect of skill differences on word reading in context among adults. Based on comparisons of readers at different skill levels within a college-student population, Ashby et al. (2005) showed differential contextual facilitation in gaze durations for average relative to high-skill readers (but only for low-frequency words, which create heightened demands for lexical access). They argued that whereas highly skilled readers are generally efficient in word recognition, average adult readers rely on sentence context to facilitate recognition of more difficult (low-frequency) words. Note, however, that university undergraduate samples, though varied, are selected into the university based in part on the ability to read and interpret texts, resulting in a base of evidence from a narrow range of high-literacy skill, relative to the larger population (National Research Council, 2012).

Accounts of skill differences have largely focused on the efficiency of word processing. Stanovich's (1980) interactive-compensatory model holds that reading fluency is underpinned by efficient context-free word-recognition processes. Similarly, Perfetti's (2007) and Perfetti and Stafura (2014) lexical quality hypothesis suggests that reading skill increases as a function of the quality of the lexical representations available to readers (also see Yap, Tse, & Balota, 2009). According to this view, those with lower levels of reading skill have a reduced ability to access word meanings that is characterized as a lack of precision (i.e., the ability to distinguish orthographic forms) and reduced flexibility of the representation (i.e., the ability to distinguish semantics). It is thought that when these processes are underdeveloped, context is used in a compensatory fashion, under the assumption that a representation of message-level context is constructed and available to support less efficient word recognition. However, it is important to note that these views were originally developed based on studies with child readers and may not necessarily be valid for low-fluency adult readers. In fact, Greenberg, Ehri, and Perrin (1997) conducted a study directly comparing low-fluency adult readers with low-fluency child readers matched on grade level. Results showed that, although adult readers were deficient in orthographic decoding, phonological awareness, and spelling skills relative to their low-fluency child controls, the adults still showed better word-recognition skill and vocabulary.

Even less is known about the joint effects of age and skill on the sensitivity to contextual constraints. Crystallized abilities, such as vocabulary knowledge, are often shown to increase through adulthood (Verhaegen, Borchelt, & Smith, 2003), an age advantage that is closely tied to reading engagement (Stanovich, West, & Harrison, 1995). Older adult readers with good vocabulary skill and high levels of print exposure have been found to show reduced effects of word frequency on reading times with commensurate increases in allocation of attention to semantic processes, (Payne et al., 2012; Stine-Morrow et al., 2008). Such findings have been interpreted as a skill-based efficiency in lexical processing that frees resources for semantic processing (cf. Gao, Stine-Morrow, Noh, Eskew Jr., 2011; Gao, Levinthal, Stine-Morrow, 2012, for an experimental demonstration). At the same time, studies using

ERPs and eye-tracking have shown qualitative differences in how individuals use context information in comprehension as a joint function of age and cognitive skills such as verbal fluency. Older adults with higher verbal fluency are more likely to show young-like patterns of using context information predictively (Federmeier et al., 2003, 2010) and age and verbal fluency also jointly determine when and how readers try to resolve lexical ambiguity (Stites et al., 2013; Stites & Federmeier, 2015). However, age comparisons across levels of verbal competence are, nevertheless, typically restricted to relatively well-educated samples with well-developed literacy skills, so that it is unclear to what extent age and reading skill interact in contributing to comprehension.

The Current Study

We used eye-tracking to examine changes in the way adults in midlife facilitate comprehension through context when contributions of knowledge and experience are highly developed, but effects of cognitive decline are less pronounced. We expected to replicate prior work showing reduced reading times, fewer regressive eye movements, and an increased probability of skipping for target words as cloze probability increased (e.g., Rayner et al., 2006). Our question was whether these contextual effects would vary with age and reading skill.

Although eye-movement data in age-comparative research have been widely used in recent years (Kemper & McDowd, 2006; Kemper et al., 2004; Stine-Morrow et al., 2010; Payne & Stine-Morrow, 2012; Whitford & Titone, 2016), to our knowledge, only three studies—the two described earlier (Kliegl et al., 2004; Rayner et al., 2006) and a recent one by Choi et al. (2017)—have used this approach to examine age effects on the sensitivity to contextual constraint. All of these studies compared eye movements of well-educated younger and older adults and showed more similarities than differences in eye-movement patterns. However, given other evidence for both increases (behavioral measures) and decreases (ERP measures) in context use in older adulthood, one possibility is that the lack of an age-related effect in eye-tracking measures across these extreme samples reflects the summation of competing sources of age-related change. Thus, a middle-aged sample may be able to reveal age-related changes due to experiences that are not mitigated by the kind of slowing or cognitive declines that impact an older adult sample.

In terms of the impact of skill, recall that less skilled readers at younger ages have also been found to show exaggerated contextual facilitation, explained as compensatory processing in the face of less well-developed lexical representations and decoding skills (Stanovich, 1980; Perfetti, 2007). If such processing operates the same way in adulthood, one might expect that age differences in contextual effects would be differentially large among adults with lower literacy skills. However, among adult readers, word recognition represents less of a bottleneck for reading comprehension, while language understanding skills show more of a contribution (Greenberg et al., 1997; Landi, 2010). Consequently, the increase in contextual facilitation effects among low-skilled readers observed in children would not necessarily be expected among adults. Thus, we were interested in variation in contextual facilitation as a window into how the balance of word-level and sentence-level comprehension processes is affected by both age and reading skill.

Method

Participants

Participants were adults (n = 80) who were diverse in age (16–64 years old), race (73.7% minority), educational attainment (2.0–15.5 years), and literacy skill (2.2–12.5 grade level on the Slosson Oral Reading Task [SORT]; Slosson & Nicholson, 1990; and 2.7–18.0 on the Woodcock–Johnson Reading Fluency task; WJ). They were recruited from adult-education programs and the local community. In our primary analyses, literacy level and age were treated as continuous variables, but to broadly characterize the sample, we present age, educational level, and ability measures for groups of subjects based on age (adopting 40 as an arbitrary cutoff between "young" and "middle-aged") and literacy (using the median reading level of 9.5 as the break point) in Table 1. Younger adults were 16 to 40 years of age, and middle-aged adults were 41 to 64 years of age. Reading level for each subject was derived from the average of grade-level estimates of the WJ task and the SORT, which represent the constructs of reading fluency and word recognition, respectively.

As shown in Table 1, the literacy groups did not differ from one another in age or education level, Fs < 1, but there were observable advantages for the high-literacy group in speed, $F(1, 76) = 4.31$, $p < .05$, crystallized ability, $F(1, 76) = 14.04$, $p < .01$, fluid ability, $F(1, 76) = 16.00$, $p < .01$, phonological awareness, $F(1, 76) = 18.87$, $p < .01$, and Rapid Automatized Naming/Rapid Alternating Stimulus (RAN/RAS) scores (Wolf & Denckla, 2005), $F(1, 76) = 6.54$, $p < .01$. The younger group had significantly better scores on speed, $F(1, 76) = 9.06$, $p < .01$, and fluid ability, $F(1, 76) = 5.04$, $p < .05$, relative to the middle-aged adults. No interactions between age and literacy skill reached significance, all Fs < 1.

Cognitive Battery

Psychomotor speed. The Letter and Pattern Comparison tasks are assessments of psychomotor speed (Salthouse, 1991). The letter-comparison task requires participants to compare strings of letters and indicate whether they are the same or different within a time limit of 30 s. Similarly, the pattern-comparison task requires participants to make judgments on two abstract line drawings. For each task, participants attempt two trials, and the score corresponds to the mean number of items correct from the two trials.

Fluid and crystallized ability. The Wechsler Abbreviated Scale of Intelligence (WASI) assesses fluid (Gf) and crystallized (Gc) intelligence (Wechsler, 1981). The assessments of Gf include the block design (i.e., arranging blocks to match a prompt within a particular time limit) and the matrix reasoning (i.e., multiple choice pattern-completion task), and assessments of Gc probe vocabulary knowledge and the ability to articulate similarities between objects.

Word identification. The SORT is a word-identification task in which the subject is presented a series of 12 grade-level lists of words and the task is to pronounce the words as accurately as possible (Slosson & Nicholson, 1990) with no time limit. The number of correct items corresponds to a grade-level estimate of reading ability.

Naming fluency. The RAN/RAS (Wolf & Denckla, 2005) requires participants to name items in sequence with speed and

Table 1
Participant Characteristics

	Low literacy				High literacy						Correlations			
	Y (n = 25)		MA (n = 19)		Y (n = 20)		MA (n = 16)		Total (n = 80)					
Measures	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	Age	Ed, level	Gc	Gf
Age	26.96	7.58	52.58	6.07	24.15	6.90	49.44	5.14	36.84	14.34		.12	.07	**−.28**
Education level	11.56	1.39	11.26	2.72	11.52	1.35	12.41	1.97	11.65	1.90	.12		**.40**	.19
Speed*	.03	.97	−.52	.76	.48	.88	−.02	.55	.00	.88	**−.34**	.02	.02	**.41**
Pattern comparison	16.78	4.53	14.87	3.98	18.85	2.97	16.59	3.45	16.81	4.02	**−.36**	−.03	.03	**.40**
Letter comparison	9.78	2.59	8.13	1.71	10.80	3.60	9.66	1.50	9.62	2.67	**−.24**	.07	.01	**.32**
Crystallized ability (Gc)*	−.34	.59	−.32	.86	.29	.69	.53	1.15	.00	.88	.07	**.40**		**.41**
Vocabulary	23.52	6.81	24.84	7.33	29.75	5.36	34.06	9.50	27.50	8.19	.19	**.42**	**.88**	**.32**
Similarities	23.68	3.12	23.16	4.00	25.80	3.81	25.50	5.62	24.45	4.17	−.07	**.28**	**.88**	**.40**
Fluid ability (Gf)*	−.04	.74	−.68	.55	.43	.84	.32	.94	.00	.87	**−.28**	.19	**.41**	
Block design	22.44	12.56	15.53	8.60	27.60	12.46	28.25	12.70	12.96	5.72	−.17	**.23**	**.43**	**.87**
Matrices	12.92	4.97	8.74	4.55	15.95	5.31	14.31	5.99	23.25	12.54	**−.32**	.10	**.28**	**.87**
Reading grade level	6.97	1.98	7.62	1.38	11.79	1.79	11.72	1.54	9.28	2.83	−.02	.18	**.47**	**.40**
SORT	7.32	2.45	8.64	2.58	11.16	1.80	12.05	1.14	9.54	2.84	.13	.20	**.37**	**.33**
WJ reading fluency	6.63	2.06	6.59	2.10	12.43	3.05	11.39	2.82	9.02	3.66	−.13	.13	**.45**	**.37**
Phonological awareness	4.40	3.94	3.62	2.21	8.12	7.09	9.94	5.59	6.31	5.52	−.02	**.23**	**.37**	**.50**
RAN/RAS	9.79	3.06	9.72	3.24	11.61	2.06	11.39	2.54	10.55	2.87	−.11	−.08	.15	.10
Reading measures														
FFD (ms)	230	21	248	36	228	32	228	42	233	33	.12	−.14	−.01	−.21
GD (ms)	327	83	339	89	276	41	279	67	307	77	.14	−.10	−.14	**−.32**
RPD (ms)	667	244	575	126	523	212	462	147	568	206	−.13	−.19	−.04	−.14
pRO	.33	.18	.27	.13	.28	.17	.26	.14	.29	.16	−.12	−.02	.08	.15
Skip	.11	.12	.16	.13	.10	.08	.13	.13	.12	.11	.13	.20	.00	.04
Comprehension	.86	.13	.88	.09	.90	.11	.95	.04	.89	.11	.20	.12	**.30**	.13

Note. SORT = Slosson Oral Reading Test; WJ = Woodcock Johnson Sound Awareness; FFD = first fixation duration; RAN/RAS = Rapid Automatized Naming/Rapid Alternating Stimulus; GD = gaze duration; RPD = regression path duration; pRO = probability of regressing out; skip = probability of skipping; Y = young; MA = middle-aged. Bolded items are significant at $p < .05$.
* Estimated as standardized composites of component measures listed right below; component measures are given as raw scores.

accuracy; there are six lists each containing a different set of items: objects, colors, numbers, letters, numbers and letters, and finally numbers, letters, and colors. The time it takes to name all the items corresponds to a grade-level estimate for each trial, with faster times corresponding to a higher reading level. Although not a reading task, this task is highly diagnostic of reading difficulty (Norton & Wolf, 2012).

Phonological awareness. The Woodcock–Johnson (WJ) Sound Awareness (Schrank, Mather, & McGrew, 2014) assesses the ability to manipulate speech sounds; this assessment includes subtasks that require rhyming, and deletion and substitution of sounds for words.

Reading fluency. In the WJ Reading Fluency task, participants are presented with a list of 98 sentences (e.g., "A fish lives on land." "Games can be played with a deck of cards." "People park their cars on top of their chimneys.") and are required to silently read and determine the truth value for as many as possible within 3 min (Schrank et al., 2014). Even highly proficient readers rarely get through the whole list of sentences. Thus, this is a measure of fluency in executing the coordinated processes that are need to understand a simple sentence (e.g., decoding, lexical access, parsing, semantic integration). The number of items correct has been normed against a grade-level estimation of reading skill.

Materials

Stimuli were 60 sentences varying in contextual constraint and expectancy (see Table 2), adapted from Federmeier et al. (2007). We chose sentences from the Federmeier et al. (2007) set that had a reading level of 4.1 or below. Thirty were created to weakly constrain the sentence-final word, and 30 were created to strongly constrain the sentence-final word. Half of each type of sentence frame was completed with the expected ending and half with an unexpected, but plausible, ending. The expected target words were always the most probable continuations, as established by norming (see Federmeier et al., 2007 for more detail). Each sentence with the target word was followed by a continuation sentence to form a short passage. There were two stimulus lists. Each participant received all the sentence frames, with the expected and unexpected endings counterbalanced across participants. Target words were controlled for length and word frequency across condition; sentences were controlled for length and grade level across condition and list. The order of sentence presentation was randomized across subjects. A comprehension question followed each sentence, with equal numbers of *YES* and *NO* answers. Questions were designed to probe information from different parts of the sentences or to require simple inferences.

Procedure

The entire session lasted approximately 2 hr. First, participants provided information about background and health and were then administered the cognitive battery, which typically took less than an hr and a half. Afterward, they completed the reading task, requiring another half hr. This study protocol was approved by the Institutional Review Board at the University of Illinois in Urbana-Champaign.

Participants read the sentences while their eye movements were monitored using an Eye-Link 1,000 Plus remote system (SR Research Ltd., Ottawa, ON, Canada). The desktop-mounted eye-tracker sampled at a rate of 500 Hz with accuracy within 0.5° of visual angle. Sentences were presented in white 20-point Courier New font on a black background on a 17-inch Dell monitor set to 1,024 × 768 resolution, and a refresh rate of 85 Hz. Participants were seated approximately 70 cm from the monitor such that the letters subtended less than 1° of visual angle. Most sentences did not fit on one line, but target words were never located at the end or beginning of a line, so as to control for line-change disruption in reading-time data. Participants placed their heads in a chinrest to minimize head movements. The experimenter then aligned and calibrated the tracker to one of the subject's eyes (starting with the right eye and moving to left eye, if necessary; of the 80 participants, 10 people distributed fairly evenly across the age and literacy groups, had their left eyes tracked). When the eye being tracked was properly calibrated, the participant could initiate each trial by pressing a button on a game console. In addition, a fixation correction was presented between each trial to verify that the tracker remained properly calibrated. In cases where the calibration was lost, the tracker was completely recalibrated before proceeding.

Results

Data-Analytic Approach

All of our variables were analyzed with linear mixed-effects (LME) models (Bates, Kliegl, Vasishth, & Baayen, 2015), to account for subject and item variability simultaneously. This also enabled to us to treat continuous data as such, rather than creating arbitrary groups based on cut-off points (e.g., age or literacy groups). The outcome of LME modeling is essentially a set of equations with parameter estimates that represent the combined effects of variables and their interactions.

We report eye-tracking measures for the target words that reflect a range of early- and late-stage processes in reading (Rayner et al., 2001; Reichle et al., 2003). First fixation duration (FFD) is the

Table 2
Examples of Stimulus Items

		Target		Cloze probability mean (range)	
Constraint	Sentence frame	Expected	Unexpected	Expected	Unexpected
Strong	As soon as they reached the sand, he stopped to take off his	Shoes	Watch	.90 (.70–1.00)	.03 (.00–.13)
Weak	They had to shampoo the new rug after the accident with the	Wine	Table	.37 (.20–.65)	.03 (.00–.15)

duration of the first fixation on a word; it tends to be sensitive to basic word characteristics such as length and frequency. Gaze duration (GD) is the sum of fixations on a word before moving to the right and is sensitive to lexical ambiguity and semantic complexity (e.g., the number of features of a word or sentence). Skipping rate (skip) is the proportion of items skipped during first-pass reading. The probability of regressing out (pRO) is the probability that the eyes move left to an earlier word from the target. Regression path duration (RPD) is the sum of durations of fixations on a region and all prior regions before the eyes move to the right. The latter two measures are thought to reflect message integration and reanalysis.

Fixations were trimmed based on the following criteria: (a) Two fixations with durations less than 80 ms and within 0.5° of visual angle were combined, and (b) Fixations shorter than 80 ms (with no close neighboring fixations) and longer than 1,000 ms were excluded from analyses. Also, RPDs longer than 5,000 ms were excluded from analyses. In total, less than 1% of the data were excluded from analysis.

Using the MIXED procedure of freedom in SAS software (Version 9.4, SAS Institute, 2015), models for FFD, GD, and RPD were fit to data by maximum likelihood estimation, and degrees of freedom for test statistics were estimated by the Satterthwaite method. Because reading times are skewed, we used a log normal distribution (i.e., logarithms of reading-time measures were computed and a normal distribution was assumed). Comprehension accuracy, regressions, and skipping were analyzed as dummy-coded (0,1) variables reflecting word-level behavior (later plotted as probabilities). Multilevel logistic regression models were fit using the GLIMMIX procedure in SAS software (Version 9.4, SAS Institute, 2015) using the LaPlace algorithm to approximate maximum likelihood estimation. As described below, there were no differences between reading-time measures of the unexpected words in the strong- and weak-constraint conditions. Therefore, we treated constraint and expectancy as the single continuous variable of cloze probability (cf. Table 2). Models included fixed effects for cloze probability, literacy, and age, as well as their interactions, and crossed random effects for subjects and items. Each of the fixed-effects variables was centered about its grand mean for ease of interpretation and modeled as a continuous predictor. Final models for each of the reading-time measures were selected by starting with the most complex models and deleting effects that were not significant based on likelihood ratio tests. Only effects with parameters that were significant ($p < .05$) were retained.

In subsequent paragraphs, we present the comprehension data followed by the analyses of the eye-tracking measures. Significant effects are summarized in Table 3.

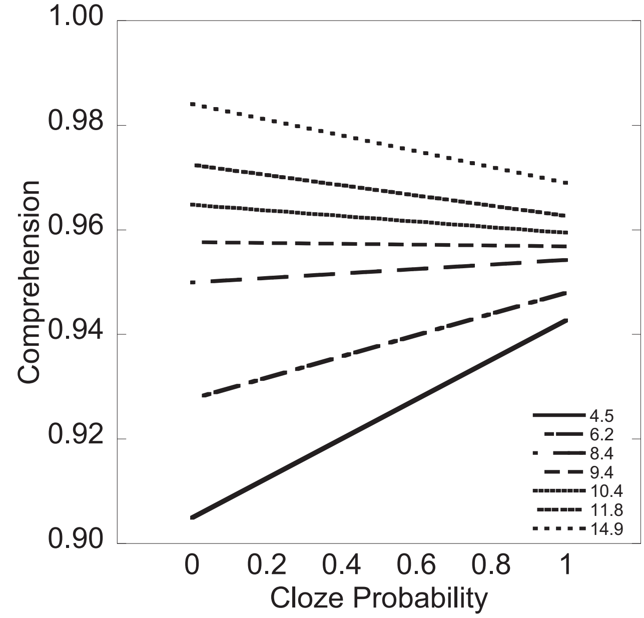

Figure 1. Comprehension accuracy as a function of cloze probability for varying levels of literacy skill (lines represent reading grade-level scores corresponding to the 5th, 20th, 35th, 50th, 65th, 80th, and 95th percentiles).

Table 3
Summary of Results

Variable	Age (Y, M)	Literacy (LL, HL)	Cloze (U, E)	Interactions
Comprehension		HL > LL		E > U greater for LL
FFD			E < U	M < Y for HL; M > Y for LL
GD		HL < LL	E < U	
RPD		HL < LL	E < U	Increase in Cloze effect with Age
pRO		HL < LL	E < U	
Skip			E > U	

Note. Y = younger adults; M = middle-aged adults; LL = low-literacy adults; HL = high-literacy adults; E = expected (high-cloze) targets; U = unexpected (low-cloze) targets; FFD = first fixation duration; GD = gaze duration; RPD = regression path duration; pRO = probability of regressing out; Skip = probability of skipping. All variables were continuous, and analyzed as such; comparisons indicated direction of significant effects and not significant differences between means.

Comprehension

Overall, comprehension was very good ($M = 0.89$, $SD = .31$), which suggested that the sentences were within the reading ability of our diverse sample. Figure 1 presents the model fit of the effect of cloze probability on comprehension as a function of reading level. In general, comprehension performance was better with increasing literacy skill, $c^2(1, N = 80) = 18.9$, $p < .01$, and age, $c^2(1, N = 80) = 9.7$, $p < .01$ (see Table 1 for group means). The effect of cloze probability alone was nonsignificant, $c^2 < 1$, but there was a significant interaction between cloze probability and literacy skill, $c^2(1, N = 80) = 5.8$, $p = .02$. The more skilled readers were clearly at ceiling on comprehension, while the lower skilled readers had particular difficulty with the low-cloze items. None of the age interactions was significant, $c^2 < 1$.

Eye-Tracking Measures

Group means for each of the eye-tracking measures are reported in Table 1. For purposes of exposition, Figure 2 presents the means for the raw data for each eye-tracking measure on the expected and unexpected words in the strong- and weak-constraint conditions. We report the cell means broken out by condition, as this reflects

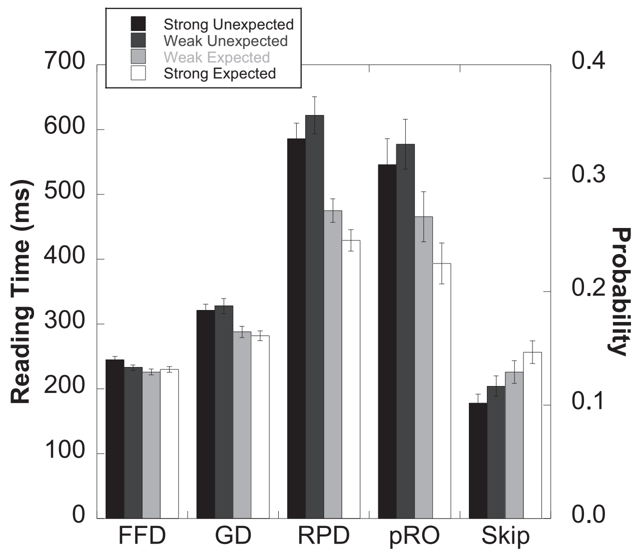

Figure 2. The effects of constraint and expectancy on the untransformed mean reading-time measures. Reading-time measures (FFD, GD, and RPD in ms) are represented on the left *y* axis, and probabilities (pRO and skip) are represented on right *y* axis. Error bars represent one *SEM*. (FFD = first fixation duration; GD = gaze duration; RPD = regression path duration; pRO = probability of regressing out; skip = probability of skipping).

our experimental design. Figure 2 shows clearly that there was no difference in reading times between the unexpected words in the strongly and weakly constraining sentences. Because previous research has shown that a strong competitor (e.g., a word activated by a strongly constraining context that does not actually appear, as in the strong constraint–unexpected condition) can disrupt comprehension (Stine & Wingfield, 1994; Wlotko et al., 2012), it is important to show that we did not find this effect. For this reason, we analyzed these data with cloze as a continuous measure to operationalize strength of semantic constraint.

In general, readers with higher literacy skill showed reduced reading times and lower probability of regression. This effect was significant for gaze duration, $c^2(1, N = 80) = 12.5$, $p < .01$; RPD, $c^2(1, N = 80) = 31.4$, $p < .01$; and regressions, $c^2(1, N = 80) = 4.1$, $p = .04$; but not for FFD, $c^2(1, N = 80) = 2.3$, $p = .13$ or skipping, $c^2(1, N = 80) = .01$, $p = .92$. Holding all other variables constant, there was no effect of age on any measure, c^2's < 1. However, as shown by the model fitting in Figure 3, the Age × Literacy Skill interaction was significant, $c^2(1, N = 80) = 3.7$, $p = .05$. Although there was no age effect overall, as reading level increased, FFDs became progressively faster, but this trend went in the other direction as reading level decreased. Although there was a numerical trend in this same direction for GD, this interaction was not significant, $c^2 < 1$. The Age × Literacy Skill interaction was also not significant for the remaining measures, c^2s < 1.

Next, we consider systematic individual differences in the effects of constraint. As expected, all of the timing measures decreased with increasing cloze probability [FFD, $c^2(1, N = 80) = 11.8$, $p < .01$; GD, $c^2(1, N = 80) = 34.8$, $p < .01$; RPD, $c^2(1, N = 80) = 93.6$, $p < .01$]. Also as expected, the pRO from the target word decreased with increasing cloze, $c^2(1, N = 80) = 27.8$, $p < .01$], and the probability of skipping increased with increasing cloze, $c^2(1, N = 80) = 12.2$, $p < .01$. The effects of cloze on FFD, GD, and probability of skipping did not vary with age or literacy skill, c^2s < 1.

However, as shown in Figure 4, the effect of cloze varied with age for regression path duration, such that the effect of cloze probability increased with age, c^2 $(1, N = 80) = 4.3$, $p < .05$. Of note, the effects of cloze and age differences in cloze did not vary with literacy skill, $c^2 < 1$.

Discussion

In recent years, eye-tracking has been increasingly employed to probe age-related differences in higher order language processes, including syntactic analysis (Kemtes & Kemper, 1997), semantic integration (Payne & Stine-Morrow, 2012; Stine-Morrow et al., 2010), ambiguity resolution (Stites et al., 2013), and interactive processes in lexical and semantic analysis (Rayner et al., 2006). These studies have largely contrasted younger and older college-educated samples, which may reveal only part of the picture, given the roles that verbal skill and reading experience play in the development of language processing (Payne et al., 2012, 2014; Stine-Morrow et al., 2008), and cognition more generally (e.g., Manly et al., 2004). In that context, the current study contributes to our understanding of the adult development of reading along a number of lines.

First, in contrast to some comparisons between younger college students and community-dwelling older adults with well-developed literacy skills (Rayner et al., 2006), we did not find evidence for ubiquitous slowing in reading processes at least into midlife. In fact, the numerical trend was for middle-aged readers to show less time spent in rereading. It is important to note, however, that we did find evidence of relatively slower processing among

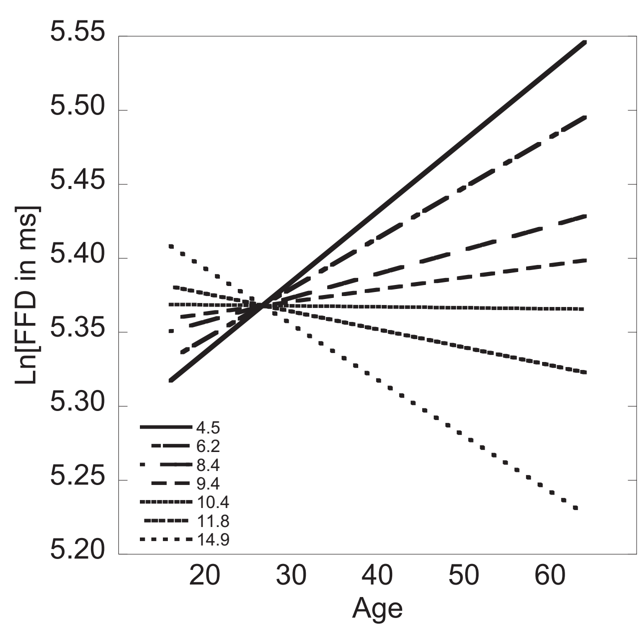

Figure 3. Natural logs of FFDs (ln[FFD]), as a function of age for varying levels of literacy skill (lines represent reading grade-level scores corresponding to the 5th, 20th, 35th, 50th, 65th, 80th, and 95th percentiles). FED = first fixation duration.

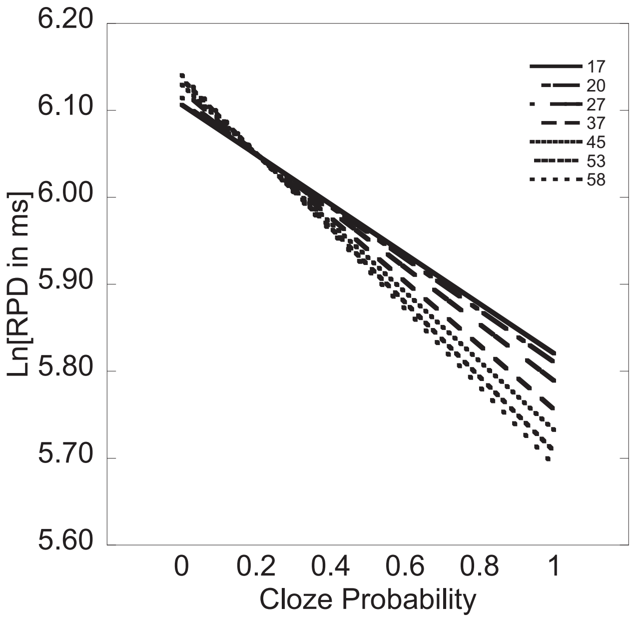

Figure 4. Natural logs of RPDs (ln[RPD]), as a function of cloze probability for varying percentiles of age (lines correspond to the 5th, 20th, 35th, 50th, 65th, 80th, and 95th percentiles of age). RPD = regression path duration.

those middle-aged adults who are poor readers. This age by literacy interaction was only detected on FFDs, and did not persist into measures of GD. Given that the speed, force, and accuracy of saccadic eye movements, especially for distances typical of reading, are relatively immune from age-related slowing (Abrams, Pratt, & Chasteen, 1998; Pratt, Dodd, & Welsh, 2006), it is unlikely that the longer FFDs among these middle-aged readers reflect slowing in oculomotor control. A more plausible account of this pattern is that continued engagement with print specifically enables pattern recognition of frequently encountered forms (as with other types of expertise; Clancy & Hoyer, 1994; Ericsson & Kintsch, 1995; Payne et al., 2014); that is, that continued development in vocabulary (Stanovich et al., 1995) affords greater automaticity of word recognition and lexical access (Lien, Allen, et al., 2006; Ruthruff, Allen, Lien, & Grabbe, 2008; Spieler & Balota, 2000). Without such consistent engagement with print, slowing is manifest. This pattern was not apparent for later-pass measures, suggesting that these experiential effects are restricted to these very early processes that depend on pattern recognition.

Second, we found that the impact of context on regression patterns increased with age. All readers allocated more time to rereading (i.e., with longer regression path durations) when encountering more unexpected than predictable words. However, this difference was greater in middle-aged than younger adults. Such increased sensitivity to context with increasing age is consistent with a number of other findings using behavioral paradigms (Madden, 1988; Stine & Wingfield, 1994; Stine-Morrow et al., 2008; Wingfield et al., 1985), and is among the first empirical demonstrations of this age by context interaction in the eye-tracking literature (see also Choi et al., 2017). So what accounts for this age-related shift? It may be that the mechanisms responsible for contextual facilitation mature with informal language experience such that with age there is an increased preference for reduced allocation of attention to more minor elements relative to higher-order knowledge structures, as seen in "knowledge-driven" reading (Miller & Stine-Morrow, 1998; Miller et al., 2004) and gist-based memory (Dennis et al., 2008). Such an interpretation must be viewed in light of other work suggesting a general age-related shift in language-comprehension mechanisms related to reduced use of prediction with age (Federmeier, Kutas, & Schul, 2010; Stites et al., 2013). Such findings imply that the increased context effect with age would not rely on predictive processing, but rather on integrative processing, an account that is consistent with these effects being localized to later-pass measures.

Our findings contrast with those from prior work comparing college-educated younger and older adults (Kliegl et al., 2004; Rayner et al., 2006), highlighting that studies of middle-aged adults can provide a unique window into multifaceted patterns of age-related change. In particular, midlife is a time when knowledge and experience are well-developed (compared with earlier in life), and declines in attention and working memory are not yet in full bloom, potentially providing the optimal time for the rapid computation of sentence meaning for impacting word-level integration.

Third, we found no evidence for an age-related increase in skipping or regressions, a pattern identified by Rayner et al. (2006) and interpreted as an age difference in reading strategy in which older adults read more superficially and then backtrack for repairs. The older sample in the Rayner et al. study was indeed older (70 to 92 years) than our oldest participant (64 years), so it may be that this is a pattern that is only manifest among the oldest readers. However, recent studies have also failed to replicate this finding (e.g., Whitford & Titone, 2016).

This research also contributes to our understanding of the nature of sentence comprehension among adults with a wider range of skill than has typically been examined. In conjunction with other work from our group (Ng, Payne, Steen, Stine-Morrow, & Federmeier, 2017), our data suggest that literacy skill impacts the use of context differentially across stages of processing. With this same population, we have found N400 amplitude patterns suggesting that low-literacy adults may be impaired in their ability to use weak contextual information to facilitate initial semantic access. In self-paced reading times, however, these less skilled readers showed persistent disruption following relatively unexpected words (whereas higher literacy readers, who showed graded N400 effects of cloze, probably did not show this continued influence of cloze probability). In the present study, we found that, although lower literacy adults were slower overall in reading than high-literacy adults, they showed similar patterns of context-based impact on the timing and patterning of their eye movements. Eye-movement measures (at least those beyond first fixations) thus seem to capture processing stages at which readers with lower literacy begin to "catch up," showing context-based effects that were apparently not fast enough to impact N400 amplitude patterns (at least in the absence of the parafoveal preview information that characterizes word-by-word reading). At the same time, our comprehension measure revealed differential sensitivity to context among less skilled readers. Whereas the level of comprehension among skilled readers was at ceiling, comprehension among low-literacy adults was somewhat lower, especially for sentences with unexpected endings or those that imposed weaker semantic constraints. Similar to what has been shown in patterns in self-paced reading times (Ng et al., 2017), therefore, it seems that lower literacy readers may experience difficulty in processing sentences in which the activation of semantic features is more diffuse or conflicting.

Lower-literacy adults were slower in reading than high-literacy adults, but we found no evidence that they used contextual information to support word-recognition processes more than high-literacy adults. This stands in contrast to research with developing readers in childhood who show exaggerated effects of context on word recognition as their decoding skills develop (Stanovich, 1980). According to the lexical quality hypothesis, struggling readers use contextual information in the sentence to supplement access to word meanings (Perfetti, 2007). However, this hypothesis may not apply to adult struggling readers because there may be more equal weight between difficulties with message-level representation and lexical analysis. Thus, while struggling child readers experience message-level facilitation on bottom-up processing, adult struggling readers might be challenged relatively more than developing child reader by message-level processing.

There are some limitations in this study. First, our materials were very simple sentences. Although this enabled us to examine reading that was well within the reading ability of our diverse sample, these were not texts that were likely to challenge or engage participants in abstract thought. Also, although it was a strength of our study to have an age-continuous sample into late midlife, the age range did not extend past the middle of the seventh decade. More work is needed to examine the impact of literacy practices and skills into the older adult age ranges (Stine-Morrow, Hussey, & Ng, 2015). It is important to note that our study is one of very few reports on language processes in midlife, and to our knowledge, the only one to examine the use of contextual constraints in sentence processing using eye-tracking with this group.

Collectively, our findings suggest a separation between reading processes that are age-sensitive and those that are specifically dependent on reading skill development with age. The age-related increase in context sensitivity was only apparent in measures reflecting processing after the initial fixation on word, in the time allocated to reread the text to integrate meaning. By contrast, it was only among the low-literacy adults that we found any evidence for age-related slowing in reading time, which was only apparent in early processes of word analysis. This pattern of findings implies that literacy experience over the life span may act to increase the automaticity of fairly low-level reading processes, but that an increase in reliance on context may reflect some other aspect of cognitive development unrelated to engagement with print. The former effect is consistent with literature on the effects of print exposure among generally proficient readers, which has shown evidence of increased efficiency of word processing among older adults (Payne et al., 2012) and increased sensitivity to statistical probabilities of syntactic forms (Payne et al., 2014). By contrast, the latter effect is consistent with a large literature suggesting that aging brings a shift toward higher order language structures for integration (Adams, Labouvie-Vief, Hobart, & Dorosz, 1990; Miller et al., 1998; Stine-Morrow & Radvansky, in press).

The current study is unusual in its examination of reading processes in terms of the interactions between age and reading skill, and it is unique in examination of the word processing of adults who are underrepresented in the language literature: middle-aged adults and adults with underdeveloped literacy skills. Our findings suggest that some aspects of context use change with age into midlife, regardless of literacy skill; and that lifelong engagement buffers against the effects of cognitive slowing in word-recognition processes.

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