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What Eye Movement Reveals Concerning Age-Related Dissociation in Syntactic Prediction: Evidence From a Verb-Final Language

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ABSTRACT

Purpose: How older adults engage in predictive processing compared to young adults during sentence processing has been a controversial issue in psycholinguistic research. This study investigated whether age-related differences in predictive processing emerge and how they influence young and older adults' construction of sentential representations in a verb-final language using the visual world eye-tracking paradigm.
Method: Twenty-five young adults and 24 older adults participated in this study. They were administered a sentence–picture matching task under active and passive conditions during which their eye movements were recorded.
Results: Older adults showed a stronger reliance on predictive processing based on probabilistic constraints compared to young adults at the second noun phrase (NP2) for both active and passive sentences. Specifically, older adults showed significantly greater target advantage looks in actives but greater distractor advantage looks in passives before encountering the verb compared to young adults, revealing older adults' stronger preference for active sentence representations. This stronger predictive processing at the NP2 among older adults engendered greater reduction in fixation proportion on the target picture at the verb only under the passive condition, suggesting that older adults experienced greater difficulties with syntactic revision and integration in passives compared to young adults.
Conclusion: The current findings support that older adults more strongly rely on predictive processing based on probabilistic constraints denoted by case markers when constructing sentential representation compared to young adults, and this processing pattern increases processing difficulties when their prediction is incongruent with linguistic input.

Linguistic changes in normal aging are multifaceted in nature. Older adults' increased linguistic experience is expected to accumulate semantic knowledge with increasing vocabulary (Baltes et al., 1999; Beier & Ackerman, 2005; Park & Reuter-Lorenz, 2009) and improved language expertise (reviewed in Diaz et al., 2016). On the other hand, their cognitive decline disrupts language processing (Burke & Barnes, 2006; Wingfield & Grossman, 2006), leading to age-related degeneration in some domains of language, such as sentence comprehension, that heavily rely on cognitive resources (Just & Carpenter, 1992).

How older adults construct a sentential representation has gained attention among researchers. In particular, age-related changes in predictive processing during the online construction of a sentential representation have been a topic of controversial debates. Recent cognitive neuroscience research proposed that older adults' decreased processing capacity engenders changes in their predictive processing mechanism with top-down predictions increasingly

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dominating (Moran et al., 2014). In psycholinguistic research, some researchers have reported that older adults rely more strongly on probability-based predictive processing compared to young adults, using the tightly integrated and particularized knowledge that they have accumulated with age (DeDe, 2014; Miller & Stine-Morrow, 1998; Rayner et al., 2006); however, others have argued that older adults are less likely to engage in predictive processing when constructing a sentential representation (Federmeier & Kutas, 2005; Federmeier et al., 2010). This discrepancy in findings raises the need for further research to specify the underlying mechanism for age-related predictive processing.

This study investigated how older adults implement predictive processing and construct sentential representations during auditory active and passive sentence processing in a verb-final language using the visual world eye-tracking paradigm (VWP). Verb-final languages could provide novel evidence for predictive processing. In verb-final languages, thematic assignment or structural analysis of the arguments is processed predictively before the verb onset because the verb is retained at sentence end. We also employed passive construction of a verb-final language. Passive construction has been recognized as a useful structure to detect sentence processing deficits in many clinical populations such as people with aphasia (Burchert & De Bleser, 2004; Caplan et al., 1997), Parkinson's disease (Colman et al., 2006), and mild cognitive impairment (MCI; Sung et al., 2020). More recently, eye movements in the VWP during active and passive sentence processing have been reported as a useful index to reveal sentence processing deficits in aphasia (Hanne et al., 2015; Mack et al., 2016; Meyer et al., 2012) and also language recovery (Mack & Thompson, 2017). However, little is known about how sensitively eye movement detects aging effects in verb-final active and passive sentence processing, particularly from the perspective of predictive processing. This study is expected to provide a novel source of evidence for age-related changes in predictive processing.

Sentence processing is thought to involve complex computations including the integration of correlated information from different domains into a syntactically licensed and meaningful interpretation (Tyler & Marslen-Wilson, 1977). In real-time auditory sentence processing, computation and integration processes take place incrementally and immediately (Kamide, Altmann, & Haywood, 2003; Trueswell et al., 1993). The properties of incrementality and immediacy have a crucial impact on real-time sentence processing. When an utterance unfolds word-by-word over time, sentential components exhibit multiple ambiguities to comprehenders due to the local indeterminacy, which is attributable to the limited amount of information (Levy, 2008; Seidenberg, 1997). Despite these temporary ambiguities, the parser immediately implements a provisional analysis on the encountered input. In addition to the provisional analysis of the current input, the parser also predicts forthcoming input at certain points in a sentence in order to increase the processing efficiency for a future input (Altmann & Kamide, 1999; Altmann & Steedman, 1988). These provisional and predictive analyses are updated as downstream information is processed.

Sentence processing models have suggested different accounts of how the language processing system predictively processes these temporary ambiguities encountered during sentence processing and constructs provisional sentential representations. There are two broad theoretical approaches: single representation versus multiple representation. According to single-representation approaches such as the garden path model, the sentence processing system activates only one syntactic representation for an ambiguous input, which is usually a simpler and preferred structure (Frazier, 1979). If the information at the disambiguation point is incompatible with the constructed representation, reanalysis occurs, which can engender processing difficulties. This syntactic processing module is encapsulated from other nonsyntactic information, and thus, a sentential structure is constructed based solely on syntactic information (Frazier, 1987). In contrast, multiple-representation approaches such as constraint-based models argue that multiple possible representations for an ambiguous input are activated in parallel as long as the processing capacity is capable of retaining them (Gorrell, 1987). In this approach, multiple sources of information such as frequency and semantic plausibility interact, constraining the interpretation probabilistically. The activation of possible representations dynamically changes as various constraints are applied while a sentence unfolds (Altmann, 1998). Processing demands are related to maintaining multiple representations and the correct interpretation is selected at the disambiguation point.

Relatedly, MacDonald et al. (1992) suggested that the manner of processing syntactic ambiguity could be affected by individuals' processing capacity. According to their capacity constrained parsing model, in the initial stage, multiple representations are constructed for an ambiguous string among both groups of comprehenders with lower and higher processing capacities. After that, individuals with a lower processing capacity are more likely to abandon the representation with the lower level of activation even when disambiguation information is not available. In contrast, individuals with higher processing capacity are more likely to maintain multiple possible interpretations. This difference in syntactic prediction, which is dependent upon processing capacity, raises the possibility of age-related differences in syntactic prediction, given that processing capacity decreases with age.

Regarding how older adults engage in predictive processing compared to young adults during sentence processing, researchers have reported controversial results. Some researchers have argued that older adults are less likely to engage in anticipatory processing. Federmeier et al. (Federmeier & Kutas, 2005; Federmeier et al., 2010) have suggested that aging has a negative influence on using the information available from contextual constraints. Federmeier and Kutas (2005) examined age-related differences when young and older adults process sentences with either a strongly constraining context or a weakly constraining context. They reported that older adults failed to show the electrophysiological evidence elicited when encountering unexpected items, reflecting reduced and delayed constraint effects in older compared to young adults. In a subsequent study, they demonstrated that these older adults' lesser engagement in predictive processing is independent of task difficulty derived from sentence type (Federmeier et al., 2010). They interpreted these results as indicating that the degree to which top-down mechanisms are automatically operated by a given input is reduced in older adults. Consequently, it is more likely that older adults engage less in predictive processing, which results in the reduced experience of either facilitation or revision costs induced by predictive processing.

In contrast, other researchers have insisted that older adults are more likely than young adults to be involved in predictive processing. They argued that older adults show a stronger propensity for predictive processing based on probabilistic constraints provided by the input during online sentence processing (Altmann & Mirković, 2009; Gibson & Pearlmutter, 1998; MacDonald, 1997). Probabilistic constraints offer information on the reliability of certain interpretations based on given linguistic cues' statistical distributions, which are formed from comprehenders' prior experience (MacDonald & Thornton, 2009; Seidenberg, 1997). For example, the first noun is more likely to be interpreted as the agent because most languages encode the first argument as the agent (Hale & Keyser, 1993) and active sentences are more frequently used than passives (E. Bates & Devescovi, 1989). In the same vein, when processing a certain structure that can be temporarily processed as either an active or a passive structure, it is more likely to be interpreted as an active sentence because the active interpretation is more reliable than the passive one.

Some researchers have insisted that older adults' stronger propensity for predictive processing based on probabilistic information is one of the compensatory mechanisms attributed to older adults' reduced processing capacity (Moran et al., 2014; Shafto & Tyler, 2014). This compensatory mechanism includes the reorganization of cognitive skills such as rendering the predictive model less complex. Instead of computing all possible alternatives, older adults rely more strongly on the tightly integrated and particularized knowledge that they have accumulated with age (DeDe, 2014; Miller & Stine-Morrow, 1998; Rayner et al., 2006). This knowledge-based process is known to reduce processing demands by diminishing the necessity of linguistic computations (Stine-Morrow et al., 2006) and further serves as one of underlying mechanisms that allows them for preserving cognitive function despite cognitive and neural changes (Moran et al., 2014).

Older adults' stronger propensity for probability-based predictive processing has been demonstrated in some age-related reading studies. Those studies have revealed that older adults use "risky" processing strategies that involve guessing upcoming words based on the knowledge of lexical cues. Rayner et al. (2006) examined older adults' reading patterns using the eye-tracking technique and found that older adults skipped more words and made more regressions back to skipped words. Rayner et al. interpreted these older adults' behavior as a compensation strategy for slowed lexical processing. DeDe (2014) extended Rayner et al.'s proposal by exploring how young and older adults implement predictive processing when processing syntactically ambiguous sentences with ditransitive or transitive subordinate verbs, using the self-paced reading paradigm. She observed that older adults read ambiguous phrases relatively faster in the transitive than ditransitive conditions, relying more heavily on their knowledge about probabilistic information of the verb for predictive processing, whereas young adults showed the opposite processing pattern, taking longer to read in the transitive condition. At the disambiguating word, both groups showed dramatic increases in reading time in the unexpected condition, but older adults' reading time was longer compared to that of young adults, showing that the reprocessing costs were greater in older compared to young adults. In order words, older adults showed fewer processing disruptions when predicting the syntactic structure correctly, whereas their processing costs for the revision process were greater than those of young adults when encountering a different structure from their prediction. DeDe interpreted these results as evidence that older adults more strongly rely on predictive processing based on probabilistic constraints of lexical cues to predict the grammatical relation of an upcoming word compared to young adults.

It has been well established that linguistic cues critically affecting sentence interpretation are different across languages. For example, in English, word order is the most valid cue to thematic role assignment, indicating that a word positioned before the verb is defined as the agent, whereas a word following the verb is defined as the patient. In other languages, however, thematic roles are assigned on the basis of different linguistic cues such as agreement marking for Italian and case marking for German (MacWhinney et al., 1984). In research on predictive processing, researchers have more focused on the effects of individual words on predictive processing

(Trueswell et al., 1993). Many studies addressing English sentences revealed that features of the verb such as subcategorization, selectional restriction, and transitivity bias serve as a source driving anticipatory processing, constraining semantic and syntactic structures of complements or arguments (Altmann & Kamide, 1999; DeDe, 2014; Seidenberg & MacDonald, 1999; Staub, 2007; Trueswell et al., 1993). Namely, comprehenders predicted the most probable semantic and syntactic structures of upcoming words based on information from the verb.

In verb-final languages that use subject–object–verb as a canonical word order, such as Korean and Japanese, however, the information from the verb cannot be a source of anticipatory processing because it is placed at the end of a sentence. Instead, morphological cues such as case markers have been reported to play critical roles in predictive processing (Kamide, Scheepers, & Altmann, 2003; M. Lee, 2019; Mitsugi, 2017). M. Lee (2019) examined whether information from case markers is used to predict a forthcoming argument in the Korean dative structure using the VWP. She found that Korean young adults make use of case information obtained from prior context (nominative and dative) to predict case information of a forthcoming argument (accusative), suggesting that case information drives anticipatory processing in a verb-final language.

This study used Korean active and passive sentences in order to investigate how older adults engage in predictive processing and construct a sentential representation. In a previous study, the sentence–picture matching task using Korean passive construction has been reported to sensitively differentiate aging populations from individuals with MCI who are at risk of dementia (Sung et al., 2020). Given the sensitivity of this paradigm to detect cognitive degeneration, there could be a possibility that it sensitively detects aging-related differences. Furthermore, online measures that will be obtained in this study may provide greater sensitivity for aging effects than offline measures.

Korean is a head-final language with an elaborate case marking system to denote a grammatical relation and a thematic role of each noun phrase (NP). In a typical active sentence, the first NP with the nominative case marker *–ka* denotes the agent, and the second NP with the accusative case marker *–lul* does the patient. The verb does not carry any morphological marker in a typical active sentence. On the other hand, Korean passive sentences have the inverse order of thematic roles (patient–agent–verb) compared to an active counterpart (agent–patient–verb) as in English. Passive sentences are denoted by oblique case marking to the second NP and verb inflection (Chang, 1996; I. Lee & Ramsey, 2001). In a typical passive sentence, the first NP denoting the patient occurs with the nominative case marker *–ka* and the second NP denoting the agent does with the dative case marker *–eykey*. Passive suffixes are attached to the verb stem. Thus, as in English, Korean passive sentences are also syntactically complex in several aspects such as the noncanonical order of thematic roles, the mismatch between grammatical relations and thematic roles (Song, 2005), and their lower frequency of occurrence (Noh, 1999; Seo, 1998).

In incremental Korean passive sentence processing, one important factor that increases processing demands is the ambiguity that case markers generate. In Korean, case markers are not tied to a specific thematic role in that a case marker is recruited to denote diverse thematic roles (Song, 2005). For example, the nominative case marker *–ka* is attached to the subjects of both active and passive sentences, implying that it could denote the agent in actives but the patient in passives. Similarly, the dative case marker *–eykey* could mark the beneficiary or recipient in actives and the agent in passives. Because the combination of the case markers *–ka* and *–eykey* can be used for both actives and passives, the exact thematic roles of arguments can be identified at the verb. Thus, thematic role mapping is accomplished at the verb in the sentence-final position as the verb serves as a disambiguation word.

The only overt difference between active and passive structures before encountering the verb is the type of case marker attached to the NP2. The accusative case marker *–lul* and the dative case marker *–eykey* are attached to the NP2 in actives and passives, respectively. Given that case markers serve as a source driving provisional and anticipatory processing before encountering the verb (M. Lee, 2019; Mitsugi, 2017) and that the parser incrementally constructs a syntactic representation based on the probabilistic information (Spivey-Knowlton et al., 1993), it is expected that the parser constructs a provisional representation based on case information. Specifically, the probabilistic information provided by case markers at the NP2 affects the construction of syntactic representation. If the parser processes active and passive structures relying on this probabilistic information, it is more likely to build a representation with active sentence structure for both the active and passive conditions before encountering the verb, given that both the accusative case marker *–lul* and the dative case marker *–eykey* could occur in actives and that actives are more frequently used than passives. According to Noh (1999), the simple active structure with the case marker *–ka* and *–lul* sequence was the most frequently used structure (38.23%). For the structure with the case marker *–ka* and *–eykey* sequence, the simple passive sentence (0.42%) was less frequently used than the dative sentence (2.73%). Thus, if the parser relies on probabilistic information provided by case markers, both active and passive sentences are more likely to be predictively processed as active sentence representations with higher probability of preactivating the active than passive structure before the verb onset. Consequently, at the verb that imposes constraints on the semantic and syntactic structures of the whole sentence, this facilitates integration in active sentences but interrupts it with greater syntactic revision costs in passive sentences. The passive suffix of the verb stem informs comprehenders that the nominative-marked argument is the patient and the dative-marked argument is the agent of the event. If a comprehender builds an active sentence representation in advance of verb onset, this should lead to them revising their initial interpretation. In this case, the revision costs should be identified at the verb.

This study employed the VWP to explore how older adults engage in predictive processing and construct a sentential representation compared to young adults. The VWP is used to examine participants' eye movement while they simultaneously observe a visual display and listen to an utterance (Tanenhaus, 2007). Eye movements in the VWP are known to be a sensitive index to assess sentence-level processing such as the construction of sentential representation involving thematic role assignments, the activation of competing representations, anticipatory processing, and ambiguity resolution (e.g., Altmann & Kamide, 1999; Dickey & Thompson, 2009). Although this paradigm has been widely used to study young adults, it has also been employed to identify dissociation between different groups such as young and older adults (Fernandez et al., 2020; Huettig & Janse, 2016), normal and clinical populations (Dickey & Thompson, 2009; Meyer et al., 2012; Thompson & Choy, 2009), and native speakers and second-language learners (Mitsugi, 2017).

Few studies have explored group differences in passive sentence processing using the VWP. Meyer et al. (2012) compared eye movements of people with agrammatic aphasia to those of controls to examine the source of passive sentence comprehension failure. They found that, unlike the control group, aphasic patients did not show any evidence of agent-first processing in any regions and fixated on the correct picture at the sentence offset even in active sentence processing. Furthermore, they failed to display target advantage looks in any regions of passive sentences. From these results, they concluded that sentence comprehension failure in people with aphasia is attributed to impaired lexical processing and integration. Mack et al. (2016) examined the test–retest reliability of the VWP in people with aphasia and unimpaired young adults to evaluate the usefulness of this paradigm as a measure of online processing and language recovery. They found that healthy young adults showed agent-first processing soon after the onset of the subject noun, and it persisted through the verb in active sentences. In passive sentences, however, they exhibited eye movement patterns reflecting agent-first processing during the onset of the subject noun and thematic reanalysis of the initial agent-first processing after the verb onset. In contrast, individuals with aphasia did not show the agent-first processing pattern and differential target advantage looks between passives and actives during sentence presentation. Instead, they exhibited target advantage looks after sentence offset, more predominantly in actives than passives. Mitsugi (2017) explored how native speakers and second-language learners of Japanese use the information from case markers to incrementally activate structural representation and predict the voice of the verb. She compared eye movement patterns of those two groups when processing Japanese active and passive sentences. The results indicated that native speakers successfully predicted a syntactic structure by exploiting the information from case markers before they encountered the verb, whereas learners were less committed to predictive processing, showing reduced efficiency in using this information as compared to native speakers. She interpreted these results as reflecting that case markers drive predictive processing in verb-final sentence processing and individuals who are less proficient in using case markers rely on the semantic information of the verb to construct sentential representations.

To our knowledge, no previous studies have explored the aging effects on verb-final sentence processing using the VWP, despite the potential contributions of both the verb-final structure and the VWP in revealing age-related changes in predictive processing. The purpose of this study is to investigate whether age-related differences in predictive processing emerge during verb-final active and passive sentence processing. Furthermore, we examined how this predictive processing impacts the construction of sentential representations. This study focused on morphosyntactic features in a verb-final language such as case markers, which are known to contribute to the incremental construction of syntactic representation. To investigate age-related differences in predictive processing, we first examined young and older adults' target advantage looks at the NP1 and NP2, at which predictive processing occurs before the verb onset. The strength of target or distractor advantage looks at the NP1 and NP2 will represent the degree of reliance on predictive processing based on case marker information. Second, to examine the impact of predictive processing on the construction of a sentential representation, we analyzed age-related differences in the fixation proportion on the target picture in each phrase. Given that predictive processing facilitates or interrupts the construction of sentential representations, target fixations reflecting the strength of predictive processing will emerge in each phrase. Considering the controversy in findings about older adults' predictive processing, there could be two possible predictions. If older adults are less likely to engage in predictive processing, they will show relatively smaller target or distractor advantages compared to young adults at the NP1 or NP2. Furthermore, they will be less likely to show the patterns of target fixations reflecting facilitation or disruption induced by predictive processing in each phrase. On the other hand, if older adults have a stronger propensity for predictive processing based on probabilistic information, they will show greater target or distractor advantage in eye movement patterns than young adults as evidence for their greater engagement in predictive processing. Furthermore, they will exhibit target fixations reflecting facilitation or disruption induced by stronger predictive processing more apparently than young adults in each phrase.

Method

Participants

A total of 49 participants took part in this study, including 25 young adults (M_{age} = 23.29 years, SD = 3.26, range: 19–32, 11 women) and 24 older adults (M_{age} = 66.78 years, SD = 3.92, range: 60–73, 17 women). A health screening questionnaire (Christensen et al., 1991) and the Korean version of the Mini-Mental State Examination (Kang et al., 2012) were administered, screening out one young adult and one older adult. Twenty-four young adults and 23 older adults were entered into the analysis. All the participants were native Korean speakers and reported no major health concerns; no history of neurological and psychiatric impairments; and no problems of vision, color perception, or hearing. The young ($M_{education}$ = 14.75 years, SD = 1.94, range: 12–19) and older ($M_{education}$ = 13.39 years, SD = 3.13, range: 9–21) groups were not significantly different in years of education, $F(1, 45) = 3.231$, $p > .05$. All participants provided written informed consent before participation. This study was approved by the Institutional Review Board on Human Subjects of Ewha Womans University.

Materials

For a sentence–picture matching task, we employed a subset of the sentence comprehension task (Sung, 2015). Experimental stimuli consisted of 128 sentences including 32 target and 96 filler sentences. Sixteen verbs allowing for semantically reversible active and passive sentences were used. For each verb, 16 active and 16 passive sentences were created as target stimuli. All the target sentences are composed of three phrases: NP1, NP2, and verb. They are all semantically reversible sentences. For the nouns, artificial humanized characters created with three different colors of yellow, blue, and black were used for the two arguments denoting the agent and patient. This was intended to minimize the effect of top-down semantic processing (Sung, 2015).

Examples for active and passive sentences are presented in Table 1. Example sentences were transliterated based on the Yale system of romanization (Martin, 1992). In Korean, a typical active sentence is composed of (a) the subject with the nominative case marker *–ka* and the agent role, (b) the object with the accusative case marker *–lul* and the patient, and (c) the verb. Passivization occurs in the way that the object (the patient) of an active sentence becomes the subject of a passive sentence and the subject (the agent) of an active sentence becomes the oblique argument marked by the dative case marker *–eykey* (I. Lee & Ramsey, 2001). The passive verb is created by attaching a suffix (e.g., *−ih*, *−hi*, *−li*, *−gih*) to a limited number of transitive verbs. Thus, a passive sentence is denoted by oblique case marking to the second NP and verb inflection (Chang, 1996; I. Lee & Ramsey, 2001). For filler sentences, we used dative and locative sentences. In addition, we included sentences with noncanonical word order. The noncanonical structures were those with the NP1 and NP2 in reverse order such as *–lul –ka* or *–eykey –ka* sequence. The types and proportion of structures used for experimental stimuli were as follows: for the target sentences, active (15.6%) and passive (15.6%); for filler sentences, noncanonical active (15.6%), noncanonical passive (14.8%), dative (14.1%), noncanonical dative (5.47%), locative (7.8%), and noncanonical locative (10.9%). The complete list of the target sentences was provided in Appendix A.

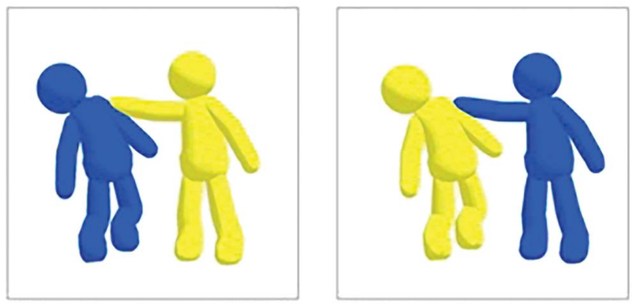
All sentences were recorded by a female native Korean speaker with a speech rate of 2.8 syllables per

Table 1. Examples of target stimuli.

Conditions	Sentence examples		
Active	The Yellow pushes the Blue.		
	Nolangi-ka	Palangi-lul	mil-ta
	the Yellow-NOM	the Blue-ACC	push-PRES-ACT-IND
Passive	The Blue is pushed by the Yellow.		
	Palangi-ka	Nolangi-eykey	mili-ta
	the Blue-NOM	the Yellow-DAT	push-PRES-PASS-IND

Note. NOM = nominative; ACC = accusative; PRES = present; ACT = active; IND = indicative mood; DAT = dative; PASS = passive.

Figure 1. Sample visual display.



second, which is within the range of normal speech production (Kwon et al., 1998). We employed the VWP with the two-picture display. For each trial, two colored pictures with opposite thematic roles were presented: One picture matches an active sentence, and the other does a passive sentence. The location of the target picture was counterbalanced across trials. Figure 1 presents an example of a visual display. The experiment was divided into four blocks including 32 sentences. Each block contained eight target (four actives and four passives) and 24 filler sentences, and no verb was repeated within the same block. The order of presenting four blocks was counterbalanced across participants. Sentences within a block were presented in random order.

Procedure

For a training session, participants were asked to look at each picture depicting an action, to read a verb displayed with a picture, and then to inform the examiner if there were any words or pictures that they did not understand. The experimenter confirmed that all participants understood all the actions and corresponding verbs. They were then asked to complete four practice trials to choose the picture corresponding to a sentence by pressing the keyboard button on the same side as the chosen picture (left vs. right side). Participants were instructed to choose a correct picture as quickly as possible after listening to a sentence.

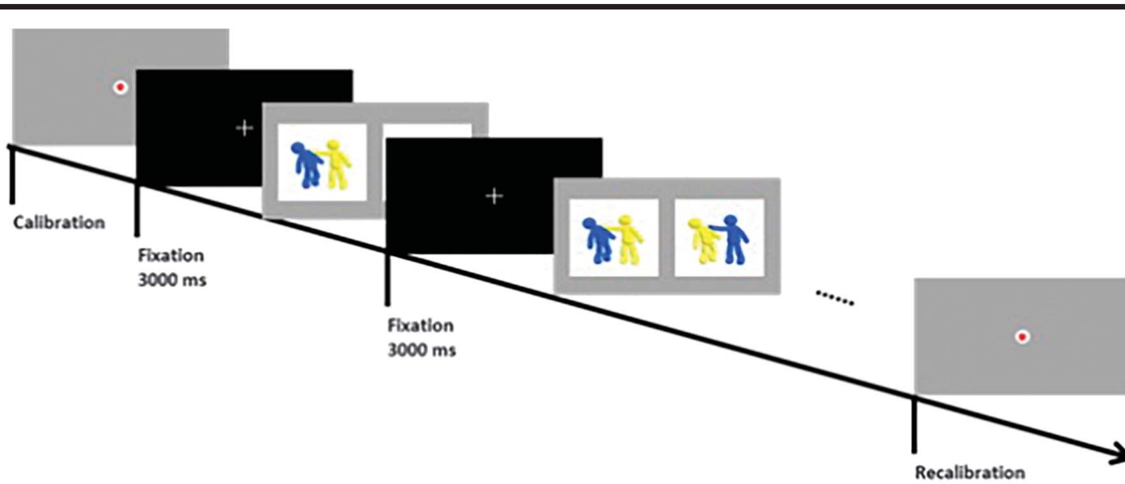
In a soundproof room, participants were seated 60–70 cm apart from the computer screen (1,920 pixels × 1,080 pixels) with their head fixed on a chinrest. Eye movements were recorded using an SMI Red (SensoMotoric Instruments) sampling at 250 Hz. Auditory sentence stimuli were presented via a speaker next to the computer screen. All the participants confirmed that the loudness of sound was appropriate for understanding before the experiment.

Each trial was displayed in the following fashion. A fixation cross appeared for 3,000 ms, and then two pictures were displayed. Five hundred milliseconds after the picture display, an auditory experimental sentence was played. The picture display was presented until the participant chose a picture. When the participants pressed the space bar key after choosing a picture, the next trial began. An example of the stimuli display is presented in Figure 2. Nonverbal tasks such as Rey figure copying and a break were administered to participants to wash out the effect of the previous block before starting a new one. The duration of performing each block is about 6–8 min. Calibration was administered before each block.

Data Analysis

To test for age-related differences in behavioral performance, we analyzed the accuracy at the trial level. The data beyond the mean accuracy ± 3 *SD* were considered

Figure 2. Display of stimuli presentation.



as outliers; no one was excluded from this outlier exclusion. For eye movement analyses, three regions of interest were defined as each phrase (NP1, NP2, and verb). Given the period of eye movement planning and execution, the data in the time window starting 200 ms after each phrase and ending 200 ms after the offset were analyzed (Altmann & Kamide, 2004). A fixation was defined as an eye gaze at the same point for 100 ms within 1° of the visual angle. Visual areas of interest were composed of two pictures (target vs. distractor), and the fixation proportion to each picture was measured. Correct responses were entered into eye movement analysis. Data from the incorrect trials were excluded (for actives, 2.17% of the data in young and 2.72% in older adults; for passives, 2.45% in young and 8.15% in older adults). Additionally, trials in which participants responded before sentence offset or eye movement data were not recorded were excluded (for actives, 3.6% in young and 9.8% in older adults; for passives, 2.1% in young and 5.7% in older adults). The percentages of eye movement data included in the analysis were 94.0% for young and 87.2% for older adults in actives and 95.3% for young and 85.9% for older adults in passives.

Two sets of eye movement analyses were conducted. In the first set of analyses, to examine whether age-related differences emerged in predictive processing as a function of sentence type, we analyzed the probability of the target advantage at the NP1 and NP2. We did not analyze target advantage at the verb, as the verb is the region in which predictive processing is resolved because the information of the thematic structure is available. The target advantage is the state of fixating on the target picture more than on the distractor and is computed as the difference between the fixation proportion on the target picture and that on the distractor. Positive values for target advantage in each condition indicate that a participant constructed the active sentence representation more than the passive one in the active condition and the passive sentence representation more than the active one in the passive condition. Negative values for target advantage indicate a stronger propensity for the distractor picture than the target picture (distractor advantage), that is, constructing the passive structure more than the active one in the active condition and the active structure more than the passive one in the passive condition. Greater target advantage indicates a stronger propensity to construct the target structure in each condition. Thus, if a comprehender has a strong propensity for predictive processing based on probabilistic constraints, it is expected that they will show greater target advantage in actives but greater distractor advantage in passives compared to individuals that have a weaker propensity for predictive processing. We computed the target advantage scores by subtracting the averaged proportions of fixations on the distractor picture from those on the target picture (Meyer et al., 2012). The average proportion of fixations was calculated by dividing the summed fixation duration by the time duration of each region of interest for each trial and sentence region. Then, we coded target advantage as a binary measure: 1 for target advantage (positive values) and 0 for distractor advantage (negative value; Mack et al., 2016). We excluded the trials with 0 value for target advantage from the analysis. In the second set of analyses, we investigated age-related differences in fixation proportion on the target picture at each sentence phrase to examine how predictive processing influences young and older adults' construction of a target sentential representation as a sentence unfolds word-by-word. The target fixation proportion was computed by dividing the summed duration of fixation on the target picture by the time duration of each region of interest for each trial and sentence region. The target fixation proportion was analyzed for the NP1, the NP2, and the verb.

For statistical analyses, we fitted mixed-effects regression models using the glmer function in the lme4 package (D. Bates et al., 2015) and lmerTest (Kuznetsova et al., 2014) in R (R Core Team, 2019). For behavioral analysis, accuracy was submitted to a mixed-effects logistic regression model that provided log odds of producing a correct response across participant groups and sentence types as the model outcome. For eye movement analyses, we fitted mixed-effects logistic regression models to assess the probability of "target advantage" at the NP1 and NP2. Regarding the analysis of fixation proportion on the target picture, generalized linear mixed-effects models were fitted with a binomial distribution and logit link function in each sentence region. In all models, group and sentence type were included as fixed effects, and for random effects, random by-participant and by-item intercepts and slopes were considered.

To determine the best-fit model, we first identified the best random-effects structure to significantly improve model fit, starting with random intercepts for participant and item. Then, we additionally fitted random slopes for sentence type across participants and items. If by-participant or by-item slopes for sentence type improved model fit compared to an intercepts-only model, the random slopes were included. If they did not, we selected an intercepts-only model at each sentence region. For fixed effects, we systematically included each predictor variable (group and sentence type) and their interaction term (Group × Sentence Type) and removed uninformative effects using the log-likelihood ratio tests with a criterion of $p < .05$ (Jaeger, 2008). The same model comparison procedures were applied to both behavioral and eye movement analyses. In all models, all categorical variables were coded using deviation coding, which enabled us to compare the mean of the predicted variable at each level to the overall mean of the variable. For parameter estimation, a maximum-likelihood estimation was used.

Results

Behavioral Results

Accuracy by participant group and sentence type in the sentence–picture matching task is summarized in Table 2. A mixed-effects logistic regression model was fitted to predict the odds of being correct as a function of participant group and sentence type. The final model contained fixed effects of group and sentence type and random intercepts for participant and item. There was a significant main effect of group (β = 0.9122, *SE* = 0.4478, *z* = 2.037, *p* = .0416). Young adults performed the sentence–picture matching task more accurately than older adults. There was a significant main effect of sentence type (β = −0.7927, *SE* = 0.2860, *z* = −2.771, *p* = .0056). Participants' accuracy was higher for active sentences compared to passive sentences. There was a tendency that older adults performed more poorly than young adults in passives compared to actives, but an interaction between group and sentence type was not statistically significant (β = 1.0532, *SE* = 0.6001, *z* = 1.755, *p* = .0792). The summary of the mixed-effects logistic regression model is displayed in Table 3. We reported the details of the model comparison procedure for accuracy in Appendix B.

Eye-Tracking Results

Target Advantage Analysis

To test whether age-related differences appear in predictive processing as a function of sentence type, a mixed-effects logistic regression model was fitted for target advantage at the NP1 and NP2. For the NP1, there were no significant effects (*p*s > .05). For the NP2, the best-fitting model included group, sentence type, and their interaction term as fixed effects and the intercepts and slopes for participants and the intercepts for items as random effects. The main effects of group (β = −0.4844, *SE* = 0.1876, *z* = −2.581, *p* = .0098) and sentence type (β = −1.3509, *SE* = 0.2327, *z* = −5.806, *p* < .0001) were significant. Critically, an interaction between group and sentence type was significant (β = 0.9258, *SE* = 0.3138, *z* = 2.950, *p* = .0032). In post hoc analysis to examine group effect in each sentence type, there were significant group effects in both actives (β = −0.4716, *SE* = 0.1823, *z* = −2.587, *p* = .0097) and passives (β = 0.4376, *SE* = 0.2015, *z* = 2.172, *p* = .0298). Specifically, older adults showed significantly greater target advantage in actives but greater distractor advantage in passives compared to young adults. Additionally, when we examined sentence type effect in each group, there were significant sentence type effects in both young adults (β = −0.4225, *SE* = 0.1506, *z* = −2.805, *p* = .0050) and older adults (β = −1.3075, *SE* = 0.1732, *z* = −7.551, *p* < .0001), indicating that there were significant differences in target advantage between actives and passives for both groups. Specifically, both young and older adults showed target advantages in actives but distractor advantages in passives.

Table 4 summarizes the mixed-effects logistic regression models of target advantage. Figure 3 shows mean target advantage scores by participant group and sentence type at the NP1 and NP2. We provided individual mean target advantage scores in Figure 4 to show how the trend of individuals' target advantages looks in each phrase.

Table 2. Accuracy by participant group and sentence type in the sentence–picture matching task.

	Young		Older	
Conditions	***M***	***SD***	***M***	***SD***
Active	97.83	4.05	97.28	3.69
Passive	97.55	3.11	91.85	12.42

Note. Values are mean percentage and standard deviation.

Table 3. Summary of the mixed-effects logistic regression model of accuracy.

Predictors	Estimate	*SE*	*z*	*p*
Intercept	3.8064	0.2897	13.140	.0000***
Group	0.9122	0.4478	2.037	.0416*
Sentence type	−0.7927	0.2860	−2.771	.0056**

Note. R model equation: Accuracy rate ~ Group + Sentence type + (1 | Participant) + (1 | Item). Reference levels are as follows: Group = older, Sentence type = active. The interaction term was excluded from the final model because it did not improve model fit. *SE* = standard error.

**p* < .05. ***p* < .01. ****p* < .001.

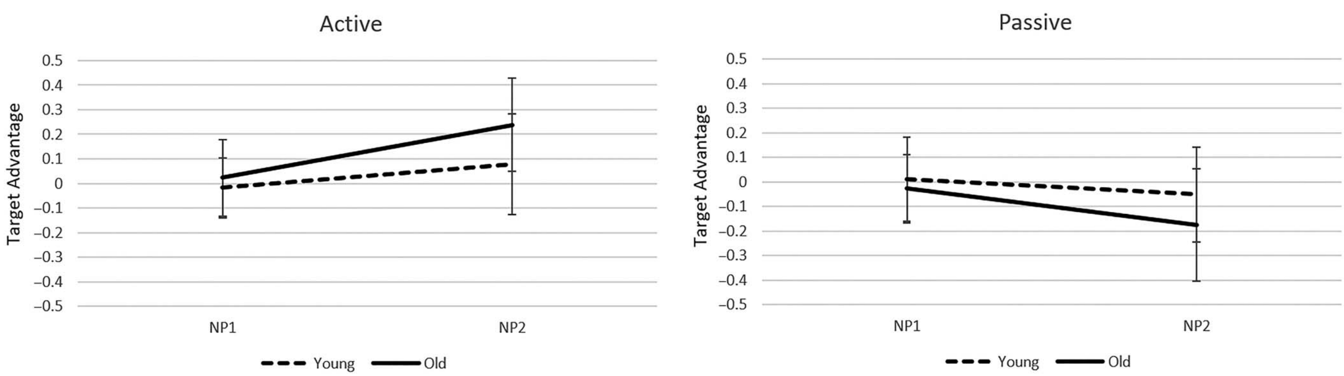
Table 4. Summary of the mixed-effects logistic regression models of target advantage at the NP1 and NP2.

Predictors	Estimate	*SE*	*z*	*p*
NP1				
Intercept	−0.0014	0.0661	−0.021	.983
NP2				
Intercept	0.7149	0.1401	5.102	.0000***
Group	−0.4844	0.1876	−2.581	.0098**
Sentence type	−1.3509	0.2327	−5.806	.0000***
Group × Sentence Type	0.9258	0.3138	2.950	.0032**

Note. R model equations: NP1 Target advantage ~ (1|Participant) + (1 | Item); NP2 Target advantage ~ Group + Sentence type + Group: Sentence type + (1 + Sentence type | Participant) + (1 | Item). Reference levels are as follows: Group = older, Sentence type = active. The fixed effects of the NP1 model were excluded from the final model because they did not improve model fit. NP = noun phrase; *SE* = standard error.

***p* < .01. ****p* < .001.

Figure 3. Mean target advantage scores by participant group and sentence type at the NP1 and NP2. NP = noun phrase.



According to the visual inspection of the overall pattern of individual target advantage scores, the age-related different pattern was apparently observed at the NP2. Older adults' greater consistency in the direction of target advantage indicated a stronger preference for the active sentence representation in both actives and passives compared to young adults. Target advantage scores at the verb revealed that individuals in both groups exhibited the apparent target advantages across sentence types when the information of the thematic structure from the verb was available. We reported the details of the model comparison procedure for target advantage in Appendix C.

Target Fixation Proportion Analysis

To identify how age-related differences in predictive processing influence young and older adults' construction of target sentential representations as a sentence unfolds word-by-word, a generalized linear mixed-effects model was fitted for the fixation proportion on the target picture in each sentence phrase. For the NP1, there were no

Figure 4. Individual mean target advantage scores by participant group and sentence type in each phrase. NP = noun phrase.

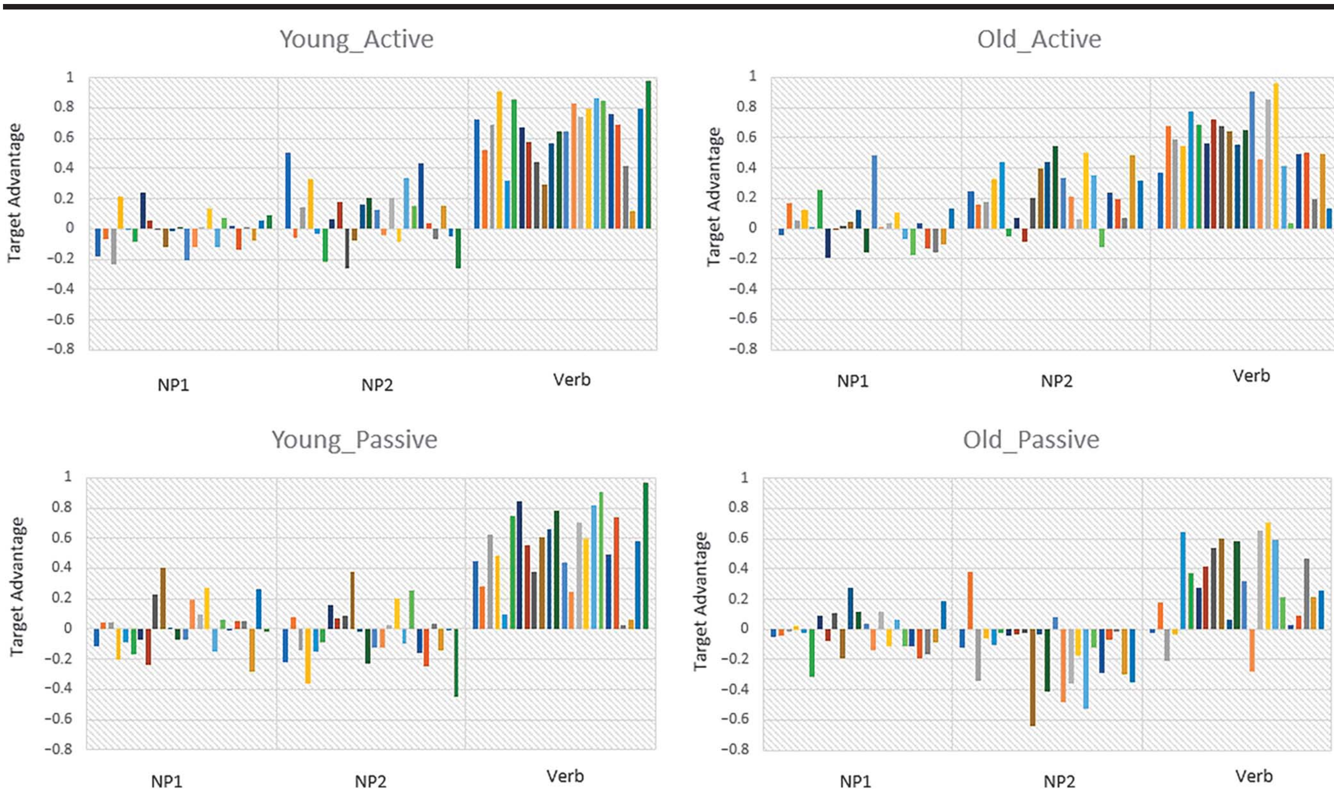


Table 5. Summary of the generalized linear mixed-effects models of target fixation proportions in each phrase.

Predictors	Estimate	*SE*	*z*	*p*
NP1				
Intercept	−0.6010	0.0566	−10.62	.0000***
NP2				
Intercept	0.1269	0.1161	1.093	.2743
Group	−0.3676	0.1597	−2.302	.0213*
Sentence type	−1.1194	0.1694	−6.607	.0000***
Group × Sentence Type	0.6382	0.2289	2.788	.0053**
Verb				
Intercept	1.0920	0.1816	6.014	.0000***
Group	0.3215	0.2569	1.252	.2107
Sentence type	−0.7542	0.1780	−4.237	.0000***
Group × Sentence Type	0.5928	0.2570	2.306	.0211*

Note. R model equations: NP1 Target fixation ~ (1 | Participant) + (1 | Item); NP2 Target fixation ~ Group + Sentence type + Group: Sentence type + (1 | Participant) + (1 | Item); Verb Target fixation ~ Group + Sentence type + Group: Sentence type + (1 | Participant) + (1 | Item). Reference levels are as follows: Group = older, Sentence type = active. The fixed effects of the NP1 model were excluded from the final model because they did not improve model fit. NP = noun phrase; *SE* = standard error.

**p* < .05. ***p* < .01. ****p* < .001.

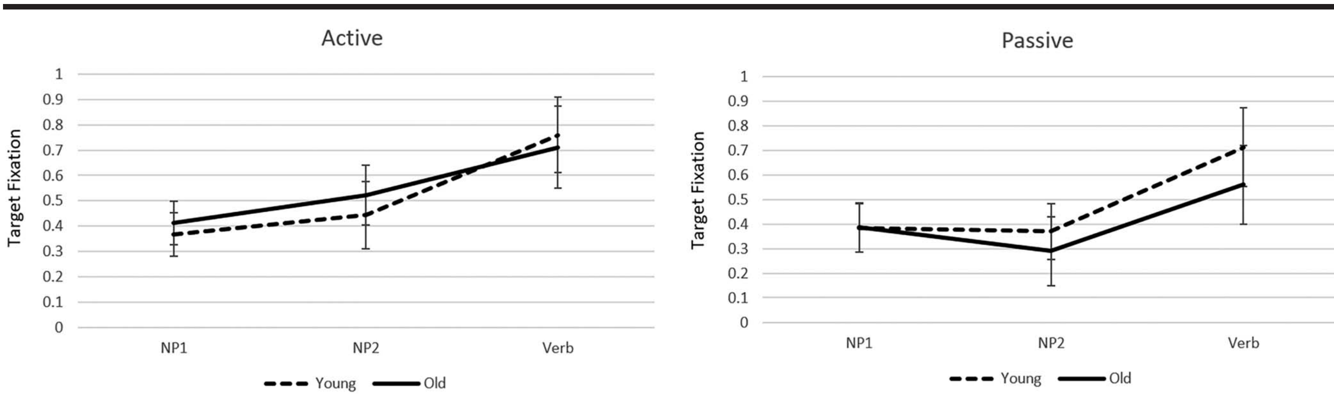
significant effects (*p*s > .05). For the NP2, the best-fitting model included group, sentence type, and their interaction term as fixed effects and the intercepts for participants and items as random effects. The main effects of group ($\beta = -0.3676$, $SE = 0.1597$, $z = -2.302$, $p = .0213$) and sentence type ($\beta = -1.1194$, $SE = 0.1694$, $z = -6.607$, $p < .0001$) were significant. There was a significant interaction between group and sentence type ($\beta = 0.6382$, $SE = 0.2289$, $z = 2.788$, $p = .0053$), demonstrating that the degree to which the fixation proportion on the target picture decreased in passives relative to actives was significantly greater in older than young adults at the NP2. Specifically, older adults made more target fixations in actives but fewer in passives compared to young adults.

At the verb, the final model included group, sentence type, and their interaction term as fixed effects and the intercepts for participants and items as random effects. The main effect of group ($\beta = 0.3215$, $SE = 0.2569$, $z = 1.252$, $p = .2107$) was not significant. The main effect of sentence type ($\beta = -0.7542$, $SE = 0.1780$, $z = -4.237$, $p < .0001$) was significant. In the passive condition, participants made significantly fewer target fixations than in the active condition across groups. There was a significant interaction between group and sentence type ($\beta = 0.5928$, $SE = 0.2570$, $z = 2.306$, $p = .0211$), indicating that the degree to which the fixation proportion on the target picture was reduced in passives relative to actives was significantly greater in older than young adults at the verb. In post hoc analysis to examine group effects in each sentence type, there was a significant group effect only in the passive condition ($\beta = 0.8789$, $SE = 0.2376$, $z = 3.699$, $p = .0002$), not in the active condition ($\beta = 0.3002$, $SE = 0.2581$, $z = 1.163$, $p = .245$). Specifically, a significant interaction between group and sentence type was attributed to older adults' significantly reduced fixation proportion on the target picture in passive sentences compared to young adults. Table 5 summarizes the generalized linear mixed-effects models of target fixation proportions. Figure 5 provides the mean target fixation proportions by participant group and sentence type in each phrase. We reported the details of the model comparison procedure for target fixation proportion in Appendix D.

Discussion

This study investigated whether age-related differences occur in predictive processing during real-time active and passive sentence processing in a verb-final language. Furthermore, we examined how different age-related patterns in predictive processing impact young and older adults' construction of sentential representations. The

Figure 5. Mean target fixation proportions by participant group and sentence type in each phrase. NP = noun phrase.



results demonstrated that older adults showed stronger predictive processing based on probabilistic information provided by case markers. Due to this propensity, older adults exhibited greater differences in the target fixation proportion between actives and passives at the NP2 and reduced target fixations at the verb only under the passive condition compared to young adults. Specifically, older adults showed a stronger preference for the active sentence representation at the NP2 for both the active and passive conditions. At the verb where disambiguation occurs, they showed significantly reduced target fixation proportion under the passive condition as evidence of greater processing costs for syntactic revision and integration.

For behavioral performance in the sentence–picture matching task, both young and older adults showed at-ceiling accuracy for active sentences ($M > 97\%$). Although older adults showed decreased performance under the passive condition compared to young adults, which seems to drive the significant main effects of group and sentence type, the interaction between group and sentence type was not significant. The reason for the interaction effect failing to reach statistical significance seems to be related to the higher variability in accuracy that older adults showed under the passive condition. Although the sentence–picture matching task using active and passive constructions was reportedly a useful tool to detect sentence comprehension deficits in clinical populations such as people with aphasia (Meyer et al., 2012), Parkinson's disease (Colman et al., 2006), and MCI (Sung et al., 2020), the current results show that behavioral accuracy obtained from this task might be a less reliable measure to detect aging effects.

The eye movement analysis demonstrates that older adults exhibited qualitatively different online sentence processing patterns compared to young adults. In order to examine age-related differences in predictive processing, we first analyzed differences in target advantage looks between young and older adults. Target advantage analysis showed that older adults more strongly engage in predictive processing based on probabilistic information compared to young adults. These age-related differences in predictive processing appeared at the NP2. A significant interaction between group and sentence type at the NP2 and significant group effects in both sentence types in the following post hoc analysis show that older adults showed significantly greater target advantage looks in actives and greater distractor advantage looks in passives compared to young adults. Although both young and older adults showed a preference for active sentence representation at the NP2—as shown in the significant sentence type effect in each group in the post hoc analysis—the degree of the preference was greater among older than young adults. These results indicate older adults' stronger preference for predictively constructing active sentence representations based on probabilistic information from case markers. Considering the probabilistic information of the case markers of the NP1 and NP2 for actives and passives, both the strings of *–ka –lul* in actives and *–ka –eykey* in passives are more likely to occur in actives than in passives (Noh, 1999), indicating that an active structure–based interpretation is more reliable than a passive structure–based one for both cases. Thus, the probabilistic information of case markers seems to impact constructing predictive sentential representation more strongly in older than young adults.

These results are in agreement with the proposal that older adults strongly rely on predictive processing based on probabilistic information during online sentence processing (DeDe, 2014; Rayner et al., 2006), but they are inconsistent with the argument that older adults less likely engage in predictive processing and are less sensitive to probabilistic information (Federmeier & Kutas, 2005; Federmeier et al., 2010). According to Rayner et al. (2006) and DeDe (2014), older adults have been reported to adopt "risky processing strategies" when reading sentences. They argued that older adults are more likely to guess upcoming words or syntactic structures based on the linguistic knowledge and revise the predicted representation if their prediction is incorrect. Rayner et al. interpreted this propensity among older adults as a compensation strategy for making up for slowed lexical processing. This knowledge-based processing is also known to reduce processing demands (Stine-Morrow et al., 2006). In this regard, the stronger predictive processing biased toward the active structure in older adults shown in this study could be interpreted as older adults' attempt to compensate for their reduced processing capacity using their accumulated knowledge.

The phenomenon that predictive processing becomes biased toward more reliable representations such as active sentence representations with age emerged at the NP2 but not at the NP1. At the NP1, there were no significant differences in eye movement. These age-related similarities and differences in predictive processing, which were observed at the NP1 and NP2, respectively, could be well explained using the capacity constrained parsing model (MacDonald et al., 1992). According to the capacity constrained parsing model, individual variability in processing capacity constrains the ways of constructing provisional representations for temporarily ambiguous strings. The model proposed that, in the initial stage of syntactic processing, both the groups with lower and higher processing capacities construct multiple representations for ambiguous strings. After that, individuals with higher processing capacities are more likely to maintain multiple possible representations until encountering the disambiguating word as long as this does not exceed their processing capacity. However, those with lower processing capacities are more likely to build a single representation with the highest possibility for an ambiguous string. As shown in the absence of significant effects at the NP1 and the plots of target advantage in Figures 3 and 4, both young and older adults did not show any biased processing toward either the active or passive representation as a group. This result prompts the speculation that both groups have a propensity for constructing multiple possible representations at the NP1, considering those representations as a target candidate. At the NP2, however, age-related group differences emerged, as shown in the significant interaction effect between group and sentence type and the visual inspection of target advantage plots in Figures 3 and 4. Older adults showed significantly greater target advantage in actives but greater distractor advantage in passives relative to young adults. Young adults' propensity for biased processing toward a certain representation was relatively weaker than that found in older adults. One possible interpretation for these differences in processing patterns between young and older adults is that young and older adults predictively process temporary syntactic ambiguities with different strategies. Young adults seem to activate multiple possible representations for ambiguous strings to a greater degree than older adults, whereas older adults seem to have a stronger propensity for resolving syntactic ambiguities in a way that selects a single representation with the highest possibility compared to young adults. Older adults showed more biased processing toward active sentence representations denoting the agent–patient or the agent–recipient configurations at the NP2 in both actives and passives, even though the configuration of the NP1 and NP2 with *–ka –eykey* sequence has the possibility of the patient–agent sequence under the passive condition. These processing patterns for the older group could be interpreted as reflecting a propensity of individuals with lower processing capacity according to the capacity constrained parsing model. In this regard, older adults' decreased processing capacity seems to render their predictive processing model less complex, and in their predictive system, probabilistic constraints based on their experience seem to play a critical role. This interplay of decreased processing capacity and increased linguistic experience is thought to induce dynamic changes in older adults' real-time sentence processing.

The finding that both young and older adults as a group did not show agent-first processing at the NP1 but did exhibit it at the NP2 in a relatively delayed fashion could be explained by certain cross-linguistic perspectives. This phenomenon is consistently observed for both actives and passives as shown in the results of statistical analysis and the plots of averaged and individual target advantage scores. Unlike the current findings, some eye-tracking studies of English sentence processing have reported that an agent-first processing bias occurs at the first noun and auxiliary in the healthy middle-age and older adults (Meyer et al., 2012) and young adults (Mack et al., 2016). These conflicting results imply that online sentence processing could occur in a language-specific manner and that accounts based on English sentence processing may be less applicable to other languages with different linguistic properties. Although a previous behavioral study reported that native speakers of Korean showed the tendency to interpret the first noun as the agent when asked to assign thematic roles to NPs without case markers in a picture-selection task (Sung et al., 2019), this result is based on the behavioral response subsequent to real-time sentence processing. It is still unknown how they process the first noun unconsciously in real-time processing. This study revealed that agent-first processing emerged at the NP2 for both actives and passives among both young and older adults. Regarding why agent-first processing did not occur at the NP1, there are a few possibilities. First, the degree to which the first noun is interpreted as the agent could differ across languages, given that critical linguistic cues affecting sentence interpretation differ across languages. Word order is important in English, whereas case markers are a more critical cue in certain other languages (MacWhinney et al., 1984). In Korean, due to the elaborate case marking system, word order is relatively flexible as long as the verb is retained at the end of the sentence. Given this flexibility of word order, the tendency to interpret the first noun as the agent might be weaker in Korean than in English. Second, relatively delayed agent-first processing in Korean might be related to the different linguistic structure between Korean and English. In English, the verb is placed at a relatively earlier position in a sentence, usually next to the subject. In Korean, however, it is positioned at sentence end. This means that, in English, the information of thematic structure is available relatively earlier than in Korean, in that the verb provides information on the thematic structure. Thus, speakers of English might start to assign thematic roles relatively earlier than speakers of Korean.

To explore how age-related different predictive processing impacts the construction of a target representation as an utterance unfolds, we analyzed age-related differences in fixation proportion on the target picture. There were no significant group or sentence type differences in target fixation proportion at the NP1. Significantly different target fixation proportion between young and older adults emerged at the NP2. A significant interaction between group and sentence type indicates that older adults exhibited greater differences in the target fixation proportion between actives and passives at the NP2 compared to young adults. These results are consistent with those of target advantage analysis, suggesting that older adults' stronger propensity for predictive processing based on probabilistic information engenders significant differences in target fixation proportion between young and older adults.

The results of target fixation analysis at the verb showed that the target fixation proportion for both active and passive sentences dramatically increases across groups, indicating that both groups successfully accomplished thematic role assignment on the basis of information from the verb morphology. The significant interaction between group and sentence type revealed that older adults exhibited a significant decrease in target fixation proportion under the passive condition. The post hoc analysis in each sentence type showed that the group effect was significant only for the passive condition. The target fixation proportion in active sentences did not differ significantly between young and older adults. This implies that older adults' predictive processing based on probabilistic information from case markers served a beneficial role in active sentence processing, allowing for older adults to show not only comparable fixation proportion at the verb but also comparable performance under the active condition in the sentence–picture matching task.

In passive sentences, older adults showed significantly reduced target fixations at the verb compared to young adults, suggesting that their stronger predictive processing based on probabilistic information before the verb onset engendered additional processing costs at the verb. Given that older adults constructed an active sentence representation to a greater degree than young adults at the NP2 for both actives and passives, they were more likely to reprocess their initial active sentence representation into a passive one at the verb under the passive condition. Revision for syntactic structure may impede efficient integration processes at sentence end and even influence behavioral performance as shown in the decreased accuracy rates among older adults under the passive condition. Our finding that older adults are more likely to engage in reprocessing in the passive condition than young adults is in line with previous reports that older adults have a stronger tendency to implement the revision process in syntactically complex sentences (DeDe, 2014; Kemper & Liu, 2007; Kemper et al., 2004). In the probabilistic view, syntactically complex sentences are more likely to include less reliable cues, given that they are used at a lower frequency. In this regard, if older adults are more reliant on probabilistic information, they are more likely to have greater possibility of reprocessing when processing less reliable linguistic cues.

This study demonstrated that examining eye movement to determine syntactic predictive processing could be a useful measure to detect aging effects. Aging-related predictive processing was associated with biased eye movement toward the preferred syntactic representation. It further impacted integration at sentence end and even behavioral performance. Specifically, correct syntactic prediction seems to facilitate integration at sentence end and increase the probability of a correct response, whereas incorrect prediction seems to engender additional revision costs. This predictive syntactic processing presupposes the application of syntactic knowledge prior to encountering linguistic input. This implies that individuals who have difficulties with using syntactic knowledge will not show such predictive processing patterns. Consistently, previous studies reported that people with agrammatic aphasia did not exhibit eye movement patterns of agent-first predictive processing, even in sentences with the basic structure such as simple actives (Mack et al., 2016; Meyer et al., 2012). This lack of predictive eye movement among people with agrammatic aphasia reflects their impairment in syntactic knowledge itself or in its use. In this regard, the current paradigm examining predictive processing based on target advantage and target fixation proportion in the VWP has the potential to assess the intactness of the ability to use syntactic knowledge and sentence processing efficiency and further to distinguish older adults with language impairment from those in healthy aging. Furthermore, the current model helps provide a more elaborate method to assess syntactic ability in the perspective of predictive processing. For example, the current paradigm might reveal a different scenario concerning the syntactic ability of individuals with MCI or early-stage dementia who manifest deficits in various cognitive domains but have relatively intact syntactic knowledge (Hodges et al., 2006). In addition, examining what syntactic representation is biasedly constructed during predictive processing helps determine what linguistic cues or information critically impact individuals' predictive processing and their construction of sentential representations.

Conclusions

This study demonstrated that older adults showed qualitative differences in online sentence processing patterns compared to young adults, relying more strongly on predictive processing based on probabilistic information denoted by case markers. These results provide convincing evidence that aging could affect the manner of constructing a sentential representation during incremental sentence processing. Older adults' reduced processing capacity engenders predictive processing patterns toward a simple and preferred representation. This becomes a smart choice when their prediction conforms to the input, but risky when it does not. Although the probability of reprocessing increases in the latter case, eliciting additional processing costs, older adults seem to take this burden, relying more on predictions based on probabilistic information. This propensity could be a driving force for older adults' success in managing everyday communication despite their decreased processing capacity because everyday communication mostly occurs in a probabilistic fashion. This study contributes to understanding how older adults build sentential representations by making use of the information of morphosyntactic cues in a verb-final language. These age-related changes in online sentence processing seem to be an adaptive response to age-related changes in processing capacity. To reduce the processing demands for linguistic computation and increase the processing efficiency, older adults seem to more strongly rely on their accumulated linguistic knowledge.

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Appendix A

List of Target Stimuli

Active			Passive		
1. The Blue holds the Black.			1. The Black is held by the Blue.		
Palangi-ka	Kemcengi-lul	cap-ta.	Kemcengi-ka	Palangi-eykey	caphi-ta.
the Blue (NOM)	the Black (ACC)	hold (PRES-ACT-IND)	the Black (NOM)	the Blue (DAT)	hold (PRES-PASS-IND)
2. The Yellow chases the Black.			2. The Black is chased by the Yellow.		
Nolangi-ka	Kemcengi-lul	ccoch-ta.	Kemcengi-ka	Nolangi-eykey	ccochkih-ta.
the Yellow (NOM)	the Black (ACC)	chase (PRES-ACT-IND)	the Black (NOM)	the Yellow (DAT)	chase (PRES-PASS-IND)
3. The Yellow pushes the Blue.			3. The Blue is pushed by the Yellow.		
Nolangi-ka	Palangi-lul	mil-ta	Palangi-ka	Nolangi-eykey	mili-ta
the Yellow (NOM)	the Blue (ACC)	push (PRES-ACT-IND)	the Blue (NOM)	the Yellow (DAT)	push (PRES-PASS-IND)
4. The Black shakes the Blue.			4. The Blue is shaken by the Black.		
Kemcengi-ka	Palangi-lul	huntul-ta	Palangi-ka	Kemcengi-eykey	huntuli-ta
the Black (NOM)	the Blue (ACC)	shake (PRES-ACT-IND)	the Blue (NOM)	the Black (DAT)	shake (PRES-PASS-IND)
5. The Black lifts the Yellow.			5. The Yellow is lifted by the Black.		
Kemcengi-ka	Nolangi-lul	tul-ta	Nolangi-ka	Kemcengi-eykey	tuli-ta
the Black (NOM)	the Yellow (ACC)	lift (PRES-ACT-IND)	the Yellow (NOM)	the Black (DAT)	lift (PRES-PASS-IND)
6. The Blue kicks the Yellow.			6. The Yellow is kicked by the Blue.		
Palangi-ka	Nolangi-lul	cha-ta	Nolangi-ka	Palangi-eykey	chai-ta
the Blue (NOM)	the Yellow (ACC)	kick (PRES-ACT-IND)	the Yellow (NOM)	the Blue (DAT)	kick (PRES-PASS-IND)
7. The Blue twists the Black.			7. The Black is twisted by the Blue.		
Palangi-ka	Kemcengi-lul	kkek-ta	Kemcengi-ka	Palangi-eykey	kkeki-ta
the Blue (NOM)	the Black (ACC)	twist (PRES-ACT-IND)	the Black (NOM)	the Blue (DAT)	twist (PRES-PASS-IND)
8. The Black steps on the Blue.			8. The Blue is stepped on by the Black.		
Kemcengi-ka	Palangi-lul	palp-ta	Palangi-ka	Kemcengi-eykey	palpi-ta
the Black (NOM)	the Blue (ACC)	step (PRES-ACT-IND)	the Blue (NOM)	the Black (DAT)	step (PRES-PASS-IND)
9. The Blue carries the Yellow on his back.			9. The Yellow is carried on his back by the Blue.		
Palangi-ka	Nolangi-lul	ep-ta	Nolangi-ka	Palangi-eykey	ephi-ta
the Blue (NOM)	the Yellow (ACC)	carry (PRES-ACT-IND)	the Yellow (NOM)	the Blue (DAT)	carry (PRES-PASS-IND)
10. The Black scratches the Blue.			10. The Blue is scratched by the Black.		
Kemcengi-ka	Palangi-lul	kulk-ta	Palangi-ka	Kemcengi-eykey	kulkhi-ta
the Black (NOM)	the Blue (ACC)	scratch (PRES-ACT-IND)	the Blue (NOM)	the Black (DAT)	scratch (PRES-PASS-IND)
11. The Black bites the Yellow.			11. The Yellow is bitten by the Black.		
Kemcengi-ka	Nolangi-lul	mul-ta	Nolangi-ka	Kemcengi-eykey	muli-ta
the Black (NOM)	the Yellow (ACC)	bite (PRES-ACT-IND)	the Yellow (NOM)	the Black (DAT)	bite (PRES-PASS-IND)
12. The Blue presses the Black.			12. The Black is pressed by the Blue.		
Palangi-ka	Kemcengi-lul	nulu-ta	Kemcengi-ka	Palangi-eykey	nuli-ta
the Blue (NOM)	the Black (ACC)	press (PRES-ACT-IND)	the Black (NOM)	the Blue (DAT)	press (PRES-PASS-IND)
13. The Yellow rolls over the Black.			13. The Black is rolled over by the Yellow.		
Nolangi-ka	Kemcengi-lul	twicip-ta	Kemcengi-ka	Nolangi-eykey	twiciphi-ta
the Yellow (NOM)	the Black (ACC)	roll (PRES-ACT-IND)	the Black (NOM)	the Yellow (DAT)	roll (PRES-PASS-IND)
14. The Yellow pokes the the Black.			14. The Black is poked by the Yellow.		
Nolangi-ka	Kemcengi-lul	ccilu-ta	Kemcengi-ka	Nolangi-eykey	ccili-ta
the Yellow (NOM)	the Black (ACC)	poke (PRES-ACT-IND)	the Black (NOM)	the Yellow (DAT)	poke (PRES-PASS-IND)
15. The Yellow pinches the Blue.			15. The Blue is pinched by the Yellow.		
Nolangi-ka	Palangi-lul	kkocip-ta	Palangi-ka	Nolangi-eykey	kkociphi-ta
the Yellow (NOM)	the Blue (ACC)	pinch (PRES-ACT-IND)	the Blue (NOM)	the Yellow (DAT)	pinch (PRES-PASS-IND)
16. The Blue pulls the Yellow.			16. The Yellow is pulled by the Blue.		
Palangi-ka	Nolangi-lul	kkul-ta	Nolangi-ka	Palangi-eykey	kkuli-ta
the Blue (NOM)	the Yellow (ACC)	pull (PRES-ACT-IND)	the Yellow (NOM)	the Blue (DAT)	pull (PRES-PASS-IND)

Note. NOM = nominative; ACC = accusative; PRES = present; ACT = active; IND = indicative mood; DAT = dative; PASS = passive.

Appendix B

Model Comparison Procedure for the Mixed-Effects Logistic Regression Model of Accuracy

We fit random intercepts and slopes for sentence type varying randomly across participants and items. Random slopes did not improve model fit compared to intercepts only model for both participants, $\chi^2(2) = 2.0799$, $p = .3535$, and items, $\chi^2(2) = 0.2274$, $p = .8925$. Thus, the random-intercepts-only model was retained. For fixed effects, we first tested whether participant group affected performance of the sentence–picture matching task. When participant group was entered as a fixed effect, this significantly improved model fit over the random-effects-only model (LogLik with random effects only = –241.80, LogLik with group = –239.76), $\chi^2(1) = 4.0818$, $p = .0434$. We examined whether sentence type affected performance of the sentence–picture matching task. A model including sentence type significantly improved model fit over the model including main effect of group (LogLik with group = –239.76, LogLik with group and sentence type = –235.68), $\chi^2(1) = 8.1572$, $p = .0043$.

We tested whether the effect of sentence type was moderated by participant group by adding the interaction term to a model with main effects of participant group and sentence type. A model including the two-way interaction between participant group and sentence type was not significantly better fit than a model with main effects only (LogLik with group and sentence type = –235.68, LogLik with Group × Sentence Type = –234.14), $\chi^2(1) = 3.0837$, $p = .0791$. Thus, for the final model, we included fixed effects of group and sentence type, and random intercepts for participant and item.

Sampling units		*N* total observations = 1,504; *N* participants = 47; *N* items = 16								
Model specification	**Model name**	**Nested/ simpler model**	**Fixed effects added**	**Random effects: Participants**	**Random effects: Items**	**Model fit: AIC**	**Model fit: BIC**	**Model fit: LogLik**	**LRT test against nested: *df***	**LRT test against nested: χ^2**
Random effects only	Null	—	—	Intercepts	Intercepts	489.60	505.55	–241.80		
Fixed effects main effects	Main Effects 1	Null	Group	Intercepts	Intercepts	487.52	508.78	–239.76	1	4.0818*
Fixed effects main effects	Main Effects 2	Main Effects 1	Sentence Type	Intercepts	Intercepts	481.36	507.94	–235.68	1	8.1572**
Fixed effects two-way interaction	Group × Sentence Type	Main Effects 2	Group × Sentence Type	Intercepts	Intercepts	480.28	512.17	–234.14	1	3.0837

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; LRT = Likelihood ratio test.

$^*p < .05$. $^{**}p < .01$.

Appendix C (p. 1 of 2)

Model Comparison Procedure for the Mixed-Effects Logistic Regression Models of Target Advantage at the NP1 and NP2

For the NP1, we fit random intercepts and slopes for sentence type varying randomly across participants and items. Random slopes did not improve model fit compared to intercepts only model for both participants, $\chi^2(2) = 0.0301$, $p = .9851$, and items, $\chi^2(2) = 0$, $p = 1$. Thus, the random-intercepts-only model was retained. For fixed effects, we first tested whether participant group influenced target advantage at the NP1. When participant group was entered as a fixed effect, this did not improve model fit over the random-effects-only model (LogLik with random effects only = –902.57, LogLik with group = –902.56), $\chi^2(1) = 0.0219$, $p = .8824$. We examined whether sentence type affected target advantage at the NP1. A model including sentence type was not significantly better fit than the random-effects-only model effect of group (LogLik with random effects only = –902.57, LogLik with sentence type = –902.42), $\chi^2(1) = 0.3042$, $p = .5813$. We tested whether the effect of sentence type was moderated by participant group by adding the interaction term to a model with random effects only. A model including the two-way interaction between participant group and sentence type did not improve model fit than a model with random effects only (LogLik with random effects only = –902.57, LogLik with Group × Sentence Type = –901.84), $\chi^2(3) = 1.4686$, $p = .6895$. Thus, the final model was the random-intercepts-only model.

C-1. Model comparison procedure for the mixed-effects logistic regression models of target advantage at the NP1.

Sampling units		***N* total observations = 1,304; *N* participants = 47; *N* items = 16**								
				Random effects		**Model fit**			**LRT test against nested**	
Model specification	**Model name**	**Nested/ simpler model**	**Fixed effects added**	**Participants**	**Items**	**AIC**	**BIC**	**LogLik**	***df***	**χ^2**
Random effects only	Null	—	—	Intercepts	Intercepts	1,811.1	1,826.7	–902.57		
Fixed effects main effects	Main Effects 1	Null	Group	Intercepts	Intercepts	1,813.1	1,833.8	–902.56	1	0.0219
Fixed effects main effects	Main Effects 2	Null	Sentence Type	Intercepts	Intercepts	1,812.8	1,833.5	–902.42	1	0.3042
Fixed effects two-way interaction	Group × Sentence Type	Null	Group × Sentence Type	Intercepts	Intercepts	1,815.7	1,846.7	–901.84	3	1.4686

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; LRT = Likelihood ratio test.

Model Comparison Procedure for the Mixed-Effects Logistic Regression Models of Target Advantage at the NP1 and NP2

For the NP2, we fit random intercepts and slopes for sentence type varying randomly across participants and items. Random slopes for participants significantly improved model fit compared to intercepts only model, $\chi^2(2) = 49.212$, $p = .0000$, but random slopes for items did not, $\chi^2(2) = 2.1742$, $p = .3372$. Thus, we included the random intercepts for participants and item and the random slopes for participants. For fixed effects, we tested whether participant group impacted target advantage at the NP2. A model including group did not improve model fit over the random-effects-only model (LogLik with random effects only = –886.71, LogLik with group = –886.57), $\chi^2(1) = 0.2964$, $p = .5861$. We evaluated whether sentence type affected target advantage at the NP2. A model including sentence type significantly improved model fit over the random-effects-only model (LogLik with random effects only = –886.71, LogLik with sentence type = –876.11), $\chi^2(1) = 21.208$, $p = .0000$. We tested whether the effect of sentence type was moderated by participant group by adding the interaction term to a model with main effects of participant group and sentence type. A model including the two-way interaction between participant group and sentence type significantly improved model fit over a model with sentence type (LogLik with sentence type = –876.11, LogLik with Group × Sentence Type = –871.91), $\chi^2(2) = 8.399$, $p = .015$. Thus, for the final model, we included main effects of group and sentence type, an interaction between group and sentence type, random intercepts and slopes for participants, and random intercepts for item.

C-2. Model comparison procedure for the mixed-effects logistic regression models of target advantage at the NP2.

Sampling units		*N* total observations = 1,315; *N* participants = 47; *N* items = 16								
				Random effects		Model fit			LRT test against nested	
Model specification	Model name	Nested/ simpler model	Fixed effects added	Participants	Items	AIC	BIC	LogLik	*df*	χ^2
Random effects only	Null	—	—	Intercepts	Intercepts	1,828.6	1,844.2	–911.32		
Random effects only	Random slopes	Null		Intercepts slopes	Intercepts	1,783.4	1,809.3	–886.71	2	49.212***
Fixed effects main effects	Main Effects 1	Random slopes	Group	Intercepts slopes	Intercepts	1,785.1	1,816.2	–886.57	1	0.2964
Fixed effects main effects	Main Effects 2	Random slopes	Sentence Type	Intercepts slopes	Intercepts	1,764.2	1,795.3	–876.11	1	21.208***
Fixed effects two-way interaction	Group × Sentence Type	Main Effects 2	Group × Sentence Type	Intercepts slopes	Intercepts	1,759.8	1,801.3	–871.91	2	8.399*

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; LRT = Likelihood ratio test.
**p* < .05. ***p* < .01. ****p* < .001.

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Model Comparison Procedure for the Generalized Linear Mixed-Effects Models of Target Fixation Proportion at the NP1, the NP2, and the Verb

For the NP1, we fit random intercepts and slopes for sentence type varying randomly across participants and items. Random slopes did not improve model fit compared to intercepts only model for both participants, $\chi^2(2) = 0.1027$, $p = .95$, and items, $\chi^2(2) = 0$, $p = 1$. Thus, the random-intercepts-only model was retained. For fixed effects, we tested whether participant group affected target fixation proportion at the NP1. A model with participant group (LogLik with random effects only = –886.53, LogLik with group = –885.96), $\chi^2(1) = 1.1457$, $p = .2845$; a model with sentence type (LogLik with random effects only = –886.53, LogLik with sentence type = –886.45), $\chi^2(1) = 0.1571$, $p = .6919$; and a model including Group × Sentence Type (LogLik with random effects only = –886.53, LogLik with Group × Sentence Type = –884.64), $\chi^2(3) = 3.7807$, $p = .2861$, did not improve model fit over the random-effects-only model. Thus, the final model was the random-intercepts-only model.

D-1. Model comparison procedure for the generalized linear mixed-effects models of target fixation proportion at the NP1.

Sampling units		*N* total observations = 1,364								
		N participants = 47; *N* items = 16								
				Random effects		Model fit			LRT test against nested	
Model specification	Model name	Nested/ simpler model	Fixed effects added	Participants	Items	AIC	BIC	LogLik	*df*	χ^2
Random effects only	Null	—	—	Intercepts	Intercepts	1,779.1	1,794.7	–886.53		
Fixed effects main effects	Main Effects 1	Null	Group	Intercepts	Intercepts	1,779.9	1,800.8	–885.96	1	1.1457
Fixed effects main effects	Main Effects 2	Null	Sentence Type	Intercepts	Intercepts	1,780.9	1,801.8	–886.45	1	0.1571
Fixed effects two-way interaction	Group × Sentence Type	Null	Group × Sentence Type	Intercepts	Intercepts	1,781.3	1,812.6	–884.64	3	3.7807

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; LRT = Likelihood ratio test.

For the NP2, we fit random intercepts and slopes for sentence type varying randomly across participants and items. Random slopes did not improve model fit compared to intercepts only model for both participants, $\chi^2(2) = 0.6634$, $p = .7177$, and items, $\chi^2(2) = 0$, $p = 1$. Thus, the random-intercepts-only model was retained. For fixed effects, we tested whether participant group affected target fixation proportion at the NP2. A model including group did not improve model fit over the random-effects-only model (LogLik with random effects only = –913.85, LogLik with group = –913.61), $\chi^2(1) = 0.4706$, $p = .4927$. We evaluated whether sentence type affected target fixation proportion at the NP2. A model including sentence type significantly improved model fit over the random-effects-only model (LogLik with random effects only = –913.85, LogLik with sentence type = –889.96), $\chi^2(1) = 47.777$, $p = .0000$. We tested whether the effect of sentence type was moderated by participant group by adding the interaction term to a model with main effects of participant group and sentence type. A model including the two-way interaction between participant group and sentence type significantly improved model fit over a model with sentence type (LogLik with sentence type = –889.96, LogLik with Group × Sentence Type = –885.85), $\chi^2(2) = 8.212$, $p = .016$. Thus, the final model included main effects of group and sentence type, their interaction term, and random intercepts for participant and item.

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Model Comparison Procedure for the Generalized Linear Mixed-Effects Models of Target Fixation Proportion at the NP1, the NP2, and the Verb

D-2. Model comparison procedure for the generalized linear mixed-effects models of target fixation proportion at the NP2.

Sampling units		*N* total observations = 1,364; *N* participants = 47; *N* items = 16								
Model specification	Model name	Nested/ simpler model	Fixed effects added	Random effects: Participants	Random effects: Items	Model fit: AIC	Model fit: BIC	Model fit: LogLik	LRT test against nested: *df*	LRT test against nested: χ^2
Random effects only	Null	—	—	Intercepts	Intercepts	1,833.7	1,849.3	–913.85		
Fixed effects main effects	Main Effects 1	Null	Group	Intercepts	Intercepts	1,835.2	1,856.1	–913.61	1	0.4706
Fixed effects main effects	Main Effects 2	Null	Sentence Type	Intercepts	Intercepts	1,787.9	1,808.8	–889.96	1	47.777***
Fixed effects two-way interaction	Group × Sentence Type	Main Effects 2	Group × Sentence Type	Intercepts	Intercepts	1,783.7	1,815.0	–885.85	2	8.212*

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; LRT = Likelihood ratio test.

*$p < .05$ ***$p < .001$.

For the verb, we fit random intercepts and slopes for sentence type varying randomly across participants and items. Random slopes did not improve model fit compared to intercepts only model for both participants, $\chi^2(2) = 0.0686$, $p = .9663$, and items, $\chi^2(2) = 0$, $p = 1$. Thus, the random-intercepts-only model was retained. For fixed effects, we tested whether participant group affected target fixation proportion at the verb. A model including group significantly improved model fit over the random-effects-only model (LogLik with random effects only = –776.90, LogLik with group = –772.74), $\chi^2(1) = 8.3122$, $p = .0039$. We evaluated whether sentence type affected target fixation proportion at the NP2. A model including sentence type significantly improved model fit over the model with group (LogLik with group = –772.74, LogLik with group and sentence type = –765.84), $\chi^2(1) = 13.808$, $p = .0002$. We tested whether the effect of sentence type was moderated by participant group by adding the interaction term to a model with main effects of participant group and sentence type. A model including the two-way interaction between participant group and sentence type significantly improved model fit over a model with group and sentence type (LogLik with group and sentence type = –765.84, LogLik with Group × Sentence Type = –763.17), $\chi^2(2) = 5.3296$, $p = .0210$. Thus, the final model included main effects of group and sentence type, their interaction term, and random intercepts for participant and item.

D-1. Model comparison procedure for the generalized linear mixed-effects models of target fixation proportion at the verb.

Sampling units		*N* total observations = 1364; *N* participants = 47; *N* items = 16								
Model specification	Model name	Nested/ simpler model	Fixed effects added	Random effects: Participants	Random effects: Items	Model fit: AIC	Model fit: BIC	Model fit: LogLik	LRT test against nested: *df*	LRT test against nested: χ^2
Random effects only	Null	—	—	Intercepts	Intercepts	1,559.8	1,575.5	–776.90		
Fixed effects main effects	Main Effects 1	Null	Group	Intercepts	Intercepts	1,553.5	1,574.4	–772.74	1	8.3122**
Fixed effects main effects	Main Effects 2	Main Effects 1	Sentence Type	Intercepts	Intercepts	1,541.7	1,567.8	–765.84	1	13.808***
Fixed effects two-way interaction	Group × Sentence Type	Main Effects 2	Group × Sentence Type	Intercepts	Intercepts	1,538.3	1,569.7	–763.17	1	5.3296*

Note. AIC = Akaike information criterion; BIC = Bayesian information criterion; LRT = Likelihood ratio test.

*$p < .05$. **$p < .01$. ***$p < .001$.