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Knowing a lot for one's age: Vocabulary skill and not age is associated with anticipatory incremental sentence interpretation in children and adults

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Abstract

Adults can incrementally combine information from speech with astonishing speed in order to anticipate future words. Concurrently, a growing body of work suggests that vocabulary ability is crucially related to lexical processing skills in young children. However, relatively little is known about this relationship with predictive sentence processing in children or adults. We explore this question by comparing the degree to which an upcoming sentential Theme is anticipated by a combination of information from a preceding Agent and Action. 48 children, aged of 3 to 10, and 48 college-aged adults' eye-movements were recorded as they looked at a four-alternative forced-choice display while they heard a sentence in which the object referred to one of the pictures (e.g. *The pirate hides the treasure*) in the presence of an Agent-related, Action-related and Unrelated distractor image. Pictures were rotated across stimuli so that, across all versions of the study, each picture appeared in all conditions, yielding a completely balanced within-subjects design. Adults and children very quickly made use of combinatory information as soon as it became available at the action to generate anticipatory looks to the target object. Speed of anticipatory fixations did not vary with age. However, when controlling for age, individuals with higher vocabularies were faster to look to the target than those with lower vocabulary scores. Together, these results support and extend current views of incremental processing in which adults and children make use of linguistic information to continuously update their mental representation of ongoing language.

One of the challenging aspects of real-time spoken language comprehension is that language must be processed incrementally and at a relatively fast speed. The meaning of a sentence evolves as it unfolds and sentential meaning cannot generally be inferred from any single word alone. In light of these challenges, it has been hypothesized that listeners utilize a strategy of continually generating expectancies about upcoming referents. Although this hypothesis remains controversial, in the past two decades a growing body of computational evidence suggests that prediction is a powerful mechanism for learning (Elman, 1990; Misyak, Christiansen, & Bruce Tomblin, 2010; Rodriguez, Wiles, & Elman, 1999), and a

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large number of empirical studies using behavioral and neurophysiological techniques have provided support for expectancy generation in sentence comprehension in adults.

Much less is known about the role of predictive processing in childhood. There are strong suggestions that prediction may underlie children's ability to segment continuous streams of auditory input into word-sized chunks (Estes, Evans, Alibali, & Saffran, 2007; Saffran, Aslin, & Newport, 1996). Nor is it known what factors might influence individual children's abilities to engage in expectancy generation, although one likely candidate is vocabulary size. For the purposes of this study, we were particularly interested in the relationship between vocabulary and predictive processing in sentences. Vocabulary size is highly associated with speed of comprehension in looking tasks (Fernald, Perfors, & Marchman, 2006; Marchman & Fernald, 2008). Moreover, there are a number of proposals in the language development literature that highlight the relationship between the lexical and grammatical development. These suggest that vocabulary knowledge may serve an important role in language tasks that require meaning and structure to be parsed and interpreted across multiple words, like in online sentence comprehension. For example, early growth of the lexicon has been argued to be the critical foundation from which basic grammar emerges (Bates & Goodman, 1997; Marchman & Bates, 1994). This proposal is supported by many observations that development of the lexicon and early morpho-syntactic competence is strongly correlated, with lexical development preceding that of grammatical development. This relationship has been noted in cross-sectional and longitudinal studies (Dale, Dionne, Eley, & Plomin, 2000; Fenson, Dale, Reznick, Bates, & Thal, 1994), and across many languages including: Icelandic (Thordardottir, Ellis Weismer, & Evans, 2002), Italian (Caselli, Casadio, & Bates, 1999), Hebrew (Maital, Dromi, Abraham, & Bornstein, 2000), and in bilingual language acquisition (Marchman, Martínez-Sussmann, & Dale, 2004) and in atypical language development (Moyle, Ellis Weismer, Evans, & Lindstrom, 2007). The idea that sentence processing may be linked to lexical knowledge is also supported by a number of grammatical theories that firmly root syntactic competence in the lexicon, such as Combinatory Categorical Grammar (Steedman & Baldridge, 2006), Head-Driven Phrase-Structure Grammar (Pollard & Sag, 1994) and Lexical Functional Grammar (Bresnan, 2001). Therefore, a central goal of this paper is to extend our understanding of the development of anticipatory sentence processing mechanisms by directly comparing the online processing of transitive sentence comprehension in 3 to 10 year old children with adults, and by testing the degree to which sentence interpretation and prediction skills are associated with differences in vocabulary level.

Much of the evidence for predictive processing in sentential comprehension in adults involves inferences made from measurement of eye-movements in response to language while viewing a visual scene. As objects are mentioned, visual attention is directed toward the spatial location of the object in the scene (Cooper, 1974; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) often before the word is even complete (Allopenna, Magnuson, & Tanenhaus, 1998; Dahan, Magnuson, & Tanenhaus, 2001). More dramatically, eye gaze may be directed towards objects even before they are mentioned (Altmann & Kamide, 1999; Altmann & Mirkovic, 2009; Kamide, Altmann, & Haywood, 2003). Eye gaze thus appears to capture moment-to-moment changes in the comprehension of language. Results from numerous studies using this technique (in the adult literature, known as the Visual World Paradigm, VWP) and others suggest that adults continuously update their mental representation of ongoing events in the sentence, and use cues from many different sources. These include semantic features (Federmeier & Kutas, 1999), event-level expectations (Bicknell, Elman, Hare, McRae, & Kutas, 2010; Hald, Steenbeek-Planting, & Hagoort, 2007; Kamide, et al., 2003; Metusalem, Kutas, Hare, McRae, & Elman, 2010) prosodic cues (Salverda, Dahan, & McQueen, 2003), phonological information (DeLong, Urbach, & Kutas, 2005; VanBerkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005) verb tense markers (Altmann & Kamide, 2007), grammatical and biological gender (Arnold, Eisenband, Brown-Schmidt, & Trueswell, 2000; Lew-Williams & Fernald, 2010; Tanenhaus, Magnuson, Dahan, & Chambers, 2000; Wicha, Moreno, & Kutas, 2004), verb selectional restrictions (Altmann & Kamide, 1999), pronominal adjectives (Sedivy, Tanenhaus, Chambers, & Carlson, 1999), verb structural biases (Trueswell, Tanenhaus, & Kello, 1993) and referential restrictions (Tanenhaus, et al., 1995). Crucially, this updating mechanism is proactive. It not only 'reacts' and 'integrates' to information it receives, but also actively generates expectations for plausible sentence continuations.

A concrete example of this process is illustrated in a series of studies reported by Kamide, Altmann and Haywood (2003), which yielded some of the earliest and most convincing support for active prediction during adult sentential comprehension. In their Study 2, participants viewed simple visual scenes containing multiple agents and objects with similar affordances, such as drinkable objects like "beer" or "milk." Participants then heard sentences such as, "The man will drink the beer" while their eye movements to this scene were simultaneously recorded. After hearing the verb "drink" but before "beer" participants fixated upon the image of the beer more than the image of the milk, indicating that their eye-movements reflected more than a simple lexical association between the verb "drink" and the upcoming object, but rather reflected predictions motivated by a combination of the prior agent and verb. Appropriate controls also established that the effect was not the result of lexical associations between "man" and "beer" or due to visual saliency of "beer" over "milk".

This result demonstrates that expectancy generation may reflect integration from multiple cues. In this case, those cues were the agent and the verb in combination. Moreover, the integration draws upon real world knowledge regarding which objects are likely patients of a verb, given the agent carrying the action denoted by the verb (see also Bicknell, et al., 2010; Hare, Jones, Thomson, Kelly, & McRae, 2009; Matsuki et al., 2011 for related findings).

Children too have been found to be able to integrate information from multiple sources to comprehend sentences in real-time. However, children are not always sensitive to the same cues as adults. For example, children under the age of 5–6 seem to show difficulty interpreting referential or extra-linguistic cues to meaning in a visual scene (Kidd & Bavin, 2005; Snedeker & Trueswell, 2004; Trueswell, Sekerina, Hill, & Logrip, 1999). Despite these limitations, children still doutilize many sources of information with great skill and speed. Both young children and adults can call upon their understanding of the syntactic and semantic meanings of verbs (Altmann & Kamide, 1999; Fernald, Zangl, Portillo, & Marchman, 2008; Nation, Marshall, & Altmann, 2003), adjectives (Fernald, Thorpe, & Marchman, 2010) and article grammatical gender (Lew-Williams & Fernald, 2010) to correctly predict an upcoming referent before it is spoken.

For example, Fernald and colleagues (Fernald, et al., 2008) have shown that children as young as 26 months are able to generate anticipatory looks to an object (e.g. "cookie") upon hearing a verb "Eat the…" much like adults (Altmann & Kamide, 1999). Moreover, electrophysiological and neuroimaging data suggest that the neural mechanisms underlying predictive skills such as noting incongruities in label-object pairings are present by the second year of life (Friedrich & Friederici, 2004, 2005; Mills, Coffey-Corina, & Neville, 1997; Travis et al., 2011). Taken together, these discoveries suggest that the skills adults use to swiftly and efficiently understand rapidly spoken sentences are in place from the earliest moments of language acquisition.

As was noted above, it seems that such integration and prediction skills are both a marker and predictor of language skill and growth, especially in relation to vocabulary. Vocabulary skill has an important relation to processing speed, as children with larger vocabularies are also quicker to comprehend spoken words. Accuracy and speed in online lexical comprehension at 25 months correlates with earlier measures of vocabulary growth between 12–24 months (Fernald, et al., 2006). Even more striking, these early differences in the speed of lexical processing at 25 months have long term consequences for language acquisition and are correlated with languages outcomes *six years later* (Marchman & Fernald, 2008). Differences in language ability are also associated with more complex measures of predictive ability. For example, the speed with which 26 month olds correctly predict the upcoming object of a verb in a sentence like "*Eat the cookie*" is also associated with concurrent vocabulary size (Fernald, et al., 2008).

It is well established that dramatic differences in vocabulary size between individuals can be observed from across the earliest stages of learning in infancy through adulthood (Fenson, et al., 1994; Verhaeghen, 2003). Children typically begin to produce their first words around the end of their first year, and vocabulary expands rapidly throughout childhood. However, the timeline and trajectory of this growth varies considerably (Fenson, et al., 1994). Whereas some children may speak their first words at 12 months and may know as many as 550 words by 24 months, others may not begin to speak for another half year, and know only 50 words by age 2 (Fenson, et al., 1994). It should be emphasized that children at both ends of this lexical learning spectrum are still considered within the "normal" range, despite this tremendous initial variability.

These differences become even more sizeable by the time children begin school. For instance, some pre-literate 5 or 6 year old children in first grade will have an expressive vocabulary of as many as 5,000 words, while others may produce only half as many words (Beck & McKeown, 1991). Across the school years, the average student will learn thousands of new words per year, amounting to several new words a day (Anglin, 1993; Graves, 1986). However, vocabulary growth in school is considerably slower for children who begin with smaller vocabularies (White, Graves, & Slater, 1990).

Finally, vocabulary growth does not stop after childhood, and vocabulary size differences continue throughout the lifespan (Verhaeghen, 2003). For instance, differences in vocabulary between individuals who have and have not attended college can be significant. One study estimated the vocabulary knowledge between adults with a high-school education and a college degree to differ 5,000 word families, which is a measurement of word knowledge that counts a root word plus its inflected forms and derivations as a single family (Zechmeister, Chronis, Cull, D'Anna, & Healy, 1995). Variability in vocabulary size is notable even in college students – a population that had been at least partially selected by performance on tests of linguistic proficiency in entrance exams (Martino & Hoffman, 2002).

Differences in early vocabulary size have important impacts on later language outcomes and school achievement. Early vocabulary growth is not only a building block for acquiring grammatical skills (Bates & Goodman, 1999; Marchman & Bates, 1994), but is also at least partially related to language and reaching achievement outcomes many years later (Cunningham & Stanovich, 1997; Marchman & Fernald, 2008). Vocabulary size has also been shown to associate with a number of other linguistic and cognitive abilities in school-age children, including phonological working memory (Gathercole & Baddeley, 1989), phonological awareness (Metsala, 1999) and reading comprehension (Cunningham & Stanovich, 1997; Stahl & Nagy, 2006). A particularly strong relationship between vocabulary level and reading comprehension has been noted since the 1920s (Whipple, 1925) see (Nation, 2009) for a review. However, early vocabulary size alone is not enough to reliably detect which individuals will be most at risk for later language and learning disabilities, as noted by numerous investigators who have tried, and largely failed, to accurately identify children who will receive later diagnoses of language impairments solely from infant measures of vocabulary (Ellis Weismer, 2007; Paul, 1996; Rescorla, 2000; Whitehurst & Fischel, 1994). In sum, vocabulary and linguistic processing speed seem to have an important relationship in early childhood, although it is likely that the relationship between the two and later outcomes may be more complex.

Taken together, these findings motivate a need for a deeper and more detailed understanding of children's predictive abilities in language comprehension, and for a better understanding of the relationship of this ability to other markers of language skill such as vocabulary. The goal of the present study is to address these gaps by asking three specific questions. First, we ask whether the results of prior studies that find evidence for linguistic prediction across one or two words scaleup to more complex language processing tasks that use more challenging stimuli. Advancing our understanding of how words are understood in sentences that require children to calculate more complex multi-word contingencies is necessary if we are to fully understand how humans can swiftly and efficiently understand complex and novel multi-word utterances, which is arguably one of the defining characteristics of language (Hockett, 1960). Secondly, in order to better understand the developmental trajectory of this skill, we examine the development of this skill across a wide range of ages. In the present study, we include participants from 3 to 10 years of age, as well as adults. Finally, because vocabulary appears to be an important marker of processing speed in young children, we ask if this relationship also exists in performance on this experimental task.

To answer these questions, we build on the task used by Kamide, Altmann, and Haywood (2003), described above. Several modifications were made to this task and extensive norming was conducted to ensure that both adults and children could comprehend the images and sentences. One important adaptation involved the layout of the visual display. Rather than provide visual scenes that included the sentential agents as was done in the original study by Kamide and colleagues (2003), we used an alternate-four choice display, in which participants were asked to indicate which image corresponded to the sentence-final target. The purpose of this modification was twofold. First, it served to reduce the visual complexity of the visual scenes, thereby increasing the likelihood that we would get clean and motivated looks to the target items from the children. Second, it allowed us to compare the relative activation and anticipation of candidate target meanings in response to the agent and action as the sentence unfolds by controlling the relationship of the distractor items to words in the sentence.

Each visual scene consisted of (1) the Target, and three types of distractors: (2) an object that was associated with the agent (Agent-Related), (3) an object that was associated with the action (Action-Related); and (4) an object that was unassociated with either the agent or action (Unrelated). Because the target was by definition associated with both agent and action, this meant that two objects were associated with the action (Target and Agent-Related pictures), and two objects were associated with the agent (Target and Action-Related pictures). Only the Target was appropriate given both the agent and the action.

This design was chosen because it additionally allows us to study in some detail the potential comprehension strategies that children and adults might employ as they interpret the sentence in real-time. One type of possible strategy would involve a staged elimination of potential sentential targets as the sentence unfolds. Consider the sample sentence *The pirate hides the treasure*, with visual display consisting of TREASURE (the Target), a (PIRATE) SHIP (Agent-Related distractor), BONE (Action-Related distractor), and CAT (Unrelated distractor). After hearing *pirate*, we might expect looks to the two objects that are associated with the agent (SHIP and TREASURE). When the action (*hides*) is heard, this makes one member of the initial cohort (SHIP) unlikely, and one might expect subsequent looks only to the target (TREASURE). This approach is analogous to the strategy proposed by the COHORT model (Marslen-Wilson, 1987) of word recognition, in which the beginning of a word activates all words that are consistent with that beginning; as the rest of the word is spoken, subsequent cues eliminate inconsistent members of the cohort until only one word—the correct word—remains active.

An alternative strategy is suggested by the TRACE and Merge/Shortlist models of speech perception (McClelland & Elman, 1986; Norris, 1994). In those models, subsequent cues may both eliminate members of the initial cohort *and* activate new words that are consistent with later cues—even if those new words are inconsistent with the initial sound of the word. Thus, as the beginning of a target word like *beaker* is heard, listeners might initially activate not only *beaker*, but also words with similar onsets, such as *beetle, bee,* etc. When the second syllable is heard, this might eliminate *beetle* and *bee.* But TRACE also predicts that new words that are consistent with that second syllable, such as *speaker,* will become active. The strategy makes it possible to recover from initial errors in perception or production, and seems in fact to provide a better fit for the empirical data (Allopenna, et al., 1998). In the case of transitive sentence processing, we might then expect that after hearing the agent and action in "The pirate hides…" example, that we may expect fixations not only to the Target object (TREASURE), but also to that of the item that is locally consistent with the action (BONE). There is increasing evidence that adults' sentential comprehension may be at least partially influenced by local coherence effects analogous to those predicted by TRACE for word recognition (Kukona, Fang, Aicher, Chen, & Magnuson, 2011; Kuperberg, 2007; Tabor, Galantucci, & Richardson, 2004). The extent to which such local strategies are applicable sentence processing is debated and whether children use different strategies than adults is unknown.

Method

Adult participants

48 native English-speaking college students (30 female) between the ages of 18–28 years (mean 21.4 years) took part in this study in return for course credit. An additional 12 participants took part and received credit, but were excluded from analysis: 11 for significant exposure to other languages in childhood, and 1 for receiving prior speech therapy. Participants had normal or corrected-to-normal vision and normal hearing, and reported no history of diagnosis or treatment for cognitive, attentional, speech or language issues.

Child participants

48 monolingual English learning children (23 female) between the ages of 3;0 to 10;0 years (mean age 6.2 years) were recruited from families in the surrounding metropolitan region (San Diego, CA). Children had either previously participated in child language research or had answered flyers and ads posted in the community. Five additional children also participated but were excluded from analysis, two for inattentiveness during testing (failing to look or respond on a majority of trials), two for receiving speech therapy, and one was not typically developing (diagnosis of PDD-NOS). Each child received a toy in return for their participation, and their families also received $10 compensation for time and travel. For children who were included in analysis, their parents reported them to have normal hearing and vision, and to be primarily hearing English at home. Parental report also indicated that they were all typically developing, without significant birth histories, no recent or chronic ear infections, and no diagnosis or treatment for other language, speech, motor, or cognitive issues.

Stimuli

Eight sets of image/sentence quartets were selected for the study. Sentence quartets were constructed by crossing two agents with two actions to create four sentences, following the design principles described in the Introduction. Images corresponded to the sentential themes in the quartet (see Figure 1 for an illustration). For example, one quartet crossed the agents (*pirate* and *dog*) with actions (*hides* and *chases*) to result in the following four sentences:

1. The pirate hides the treasure.
2. The pirate chases the ship.
3. The dog hides the bone.
4. The dog chases the cat.

The corresponding target object images for each sentence would be: TREASURE, SHIP, BONE and CAT, respectively, and participants would see all four images concurrently. For any individual sentence, each image would correspond to one of the four image conditions (Target, Agent-Related, Action-Related, Unrelated). In a sentence like, "*The pirate hides the treasure*," TREASURE would be the Target image, SHIP would be the Agent-Related image, the BONE would be the Action-Related image, and CAT would be the Unrelated distractor. Across each quartet, each image would appear in each condition once, thus yielding a completely balanced design (see Figure 1 for further illustration). Each word and each image thus serves as its own control across multiple lists in which the role of the word and object changes. In this way, intrinsic differences between salience or attractiveness of words and objects were exactly balanced across lists. Visual images were selected to be typical exemplars of target items and were photo-realistic images. Images were then edited to fit within a 400 × 400 pixel square, and objects were placed on a light background.

Norming

Prior to the study, we conducted two norming experiments to evaluate whether our stimuli would be familiar to young children. First, to ensure that the images and their labels were known and recognizable, we asked 3 and 4 year old children (who did not participate in the final experiment) at preschools to select a named image when it appeared along with the other images in each quartet. The images were recognized with a very high level of accuracy on this task (>95%). Secondly, we normed these sentence/image pairs to make sure children would have the requisite world knowledge to pick the correct target if only given the agent and action in an offline picture selection task. Preschool children (aged 3 and 4) were asked to judge which would be the likely target picture in each image quartet when only given the agent and action like "*Which one would a pirate chase?*" or "*Which one does a dog hide?*" Performance on this task was also very high (90%). Quartets were not selected for the eye-tracking study if any single image in the quartet was not appropriately selected by at least 70% of preschoolers tested. We began the norming process with 12 sentence/image quartets, but 4 did not meet our norming criteria for final selection in the study, yielding 8 quartets.

The auditory stimuli were recorded by a female native English speaker (AB) in a child-directed voice and sampled at 44,100 Hz on a single channel. Each sentence was edited using Praat audio editing software (Boersma, 2001). First, the onsets of each word (Article 1, Agent, Action, Article 2, and Target) were marked and the word duration was normalized to the mean duration of all words in the same sentential position. In cases where actions included a particle like *jump into,* the action duration was marked to include the duration of the verb and particle. The mean intensity of all sentences was then normalized to 70 dB. This arrangement yielded 32 sentences of equal length, in which the onset of each word was standardized across all sentences. This was done to ensure that participants were given the same amount of time in each sentence to use the Agent and Action information to anticipate the Target. The sentential word durations were as follows: Article 1: 134 ms, Agent: 768 ms, Action: 626 ms, Article 2: 141 ms, Target: 630 ms. The final experimental sentences were then judged by several listeners who were unfamiliar with the goals of the study to sound natural. The sound files were presented to participants via headphones, so that the same stimulus was presented to each ear. The experimental sentences are listed in Appendix A.

In any one version of the study, participants heard 16 out of 32 sentences. Each quartet of four objects was seen twice, with two out of the four possible sentences for each set presented. Across all versions, the position of each object was presented with equal frequency in each quadrant, and in each version, the target image appeared in each quadrant an equal number of times.

Procedure

Experimental task

Participants were seated in a comfortable chair in front of a 17” LCD display, and the eyetracker was focused and calibrated. Stimuli were presented using a PC computer running SR Research Eyelink Experiment Builder software (2011). Participants were told they would be seeing pictures and listening to sentences, and were either told to point (children) or click using the mouse (adults) on the picture that “goes with the sentence.” It was expected that participants would point or click on the sentence final object, which was the target of the action; indeed, this is what participants did. They were given one practice trial before starting the study. Before the start of the experimental trials, a manual 5-point calibration and validation routine was performed, using a standard black-and-white 20-point bull’s-eye image. Before each trial, participants where shown the same centrally located bull’s-eye image, which they were instructed to fixate upon before starting the trial. This dot also served as a drift-correction dot before each trial. Once they had fixated on this location, the experimenter began the trial.

Participants were shown the set of four images for 2000ms before sentence onset, and the images remained on the screen after sentence offset until the participant had selected an image from the array with the mouse or by pointing. Recalibration of the eyetracker was performed between trials if necessary, although this was rarely needed. Participants were given a break halfway through the study. This portion of the experiment lasted 5–10 minutes.

Eye-movement recording

Eye-movements were recorded using an Eyelink 2000 Remote Eyetracker with remote arm configuration (SR Research, Ltd) at 500 Hz. Since the physical size of our adult and child participants varied considerably, we individually adjusted the position of the display using a remote-arm configuration of the eyetracker such that the display and eye-tracking camera were placed 580–620 mm from the participant’s face. Head and eye-Sentence Interpretation 21 movements were automatically tracked by the eyetracker system with the use of a target sticker affixed to the participant’s forehead. This arrangement allowed for stable tracking even during some movement and shifting of each participant’s position relative the camera and display.

Fixations were recorded in each trial from the onset of the images, until the participant or experimenter clicked on the selected picture. The recorded eye-movements were automatically classified as saccades, fixations and blinks using the eyetracker’s default threshold setting. Offline, the data were binned into 10ms intervals, over which subsequent analyses were performed.

Offline measurements

After the completion of the eyetracking task, participants were then administered two offline language measures: 1) The Peabody Picture Vocabulary Test, Version 4 (PPVT-4; Dunn & Dunn, 2007)) and 2) the Sentence Completion Subtest of the Comprehensive Assessment of Spoken Language (CASL:SC; Carrow-Woolfolk, 1999). The PPVT-4 is a norm-referenced test designed to estimate receptive vocabulary for standard American English in participants between 2 and 90 years. The test contains 220 test items arranged in order of increasing difficulty with age-appropriate starting points. Each item has 4 colorful illustrations arranged in a multiple-choice format. The participant's task is to select the picture considered to correspond to the best meaning of a stimulus word presented orally by the examiner. The CASL:SC test contains 60 items of increasing difficulty, with various age-appropriate levels. In each item, the examiner reads a sentence, leaving off the final word. The participant's task is to provide any semantically and syntactically appropriate word to fit the context.

Results

Behavioral Accuracy

In order to ensure that adults and children understood the sentences and task, we first examined their accuracy to select the correct target picture. Accuracy was very high on the task in both groups, and very few errors were made in selecting the correct target picture. Across all adults, there were 4 incorrect responses (99.5% correct), and there were 20 incorrect responses in children (97.4% correct). All reported results and analyses below are conducted with these incorrect responses removed.

Timecourse measurements

In order to examine the timecourse of incremental sentence processing in adult and child groups, we calculated the mean proportion of time spent fixating to the Target, Agent-Related, Action-Related and Unrelated images at each 10ms time window across all adult participants (Figure 2a) and children (Figure 2b). Further, in order to inspect the data for potential developmental and vocabulary-related differences in processing, we split the child participants into older (aged 6;5 to 10;0) and younger (aged 3;0–6;3) age groups (Figure 3), and divided adults and children into High and Low vocabulary groups according to a median split of age-normalized PPVT (Figure 4) and age-normalized CASL:SC scores (Figure 5). Relevant demographics and characteristics children in each median-split group are reported in Table 1

These timecourse plots illustrate several interesting fixation patterns. Most prominently visible is the robust acceleration of (anticipatory) fixations to the Target object that begins as the verb is spoken. Additionally, looks to the Agent-Related and Action-Related objects also increase after the agent and action onset, respectively. Notably, the timing at which fixations to the Target object diverges from looks to other items, especially the Agent-Related item, visibly varies between age and vocabulary groups.

Timecourse of looks to the target—We initially characterized the timing of these apparent differences in fixation timing between various groups, by conducting point-by-point t-tests at each 10ms bin between mean fixation proportions to the Target object, and fixations to the Agent-Related item, because this was the second most highly fixated object in each group. In order to minimize the possibility that differences measured by these multiple t-test comparisons might have arisen by chance, we report the earliest time at which minimum of five subsequent and consecutive one-tailed t-tests with alpha level of $p<0.05$ indicate a significant positive difference between fixations to the Target and other items.

According to these analyses, the time at which fixations to the Target diverges varies considerably between adults (1220ms) and children (1420ms). Though these differences are smaller between older and younger children (1410 and 1460ms, respectively). Adults with higher and lower (age-normalized) vocabulary scores show some difference in Target divergence times (1210ms vs. 1300ms, respectively)1, and these values are very similar for high and low sentence completion groups (1220ms vs. 1300ms). The Target divergence times are quite marked between children with higher (1220ms) vs. lower (1520 ms) (age-normalized) vocabularies. Relatively smaller, though still sizeable differences in Target divergence were also found on the sentence completion measure in children (high: 1320ms; low: 1510ms).

This preliminary inspection and description of the timecourse between groups indicated that there were differences in the timing of anticipatory looking to the Target. Since these differences are revealed by a measure of the overall proportion of time spent fixating on the object, there are a number of ways these timing differences might have arisen. For one, it is possible that they are due to a difference in the speed in initial looking to the Target object. Alternatively, the mean duration or number of individual fixations might vary. In the next set of analyses, we investigate these various possibilities.

Timing of initial looks: In order to examine if the observed timing differences arose from differences in the speed at which each group initially looked to the Target, we measured the latency of the initial saccades that landed on the Target object after the Action onset. Children initially fixated to the target more rapidly than adults, $t(94)=2.057$, $p=0.04$. Older children were significantly faster than younger children to fixate on the Target, $t(46)=2.28$, $p=0.03$, as were individuals with higher age-normalized vocabularies, $t(94)=2.24$, $p=0.03$, while individuals with higher sentence completion scores were marginally faster to fixate on the Target, $t(94)=1.8$, $p=0.07$.

Duration of looking: Next, we asked whether group differences in looking to the Target might be driven by variation in the average individual fixation time. This was measured by calculating the total time spent fixating on the Target in the period from action word onset to target word offset and dividing this by the total number of fixations generated to the Target image in this period. There were no group differences in any age, vocabulary or sentence completion comparison examined with this measure.

Number of fixations: Finally, we asked if the total number of fixations to the Target varied between groups by measuring the overall number of fixations to the Target from action word onset to target offset. Children with higher vocabulary, $t(46)=3.298$, $p=0.0019$, and sentence completion scores, $t(46)=3.350$, $p=0.0016$, made a greater number of fixations to the Target object than their lower scoring peers. There were no other group effects for adults, or across age groups.

Associations between anticipatory fixations, age, and measures of linguistic ability

The above analyses explore group differences across measures that capture looking behaviors across time windows that precede and follow the onset of the target word – i.e.

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[1] These results are identical when using raw vocabulary and sentence completion scores; age-normalized scores are reported to maintain standardized analysis procedures between adults and children

using eye-movement measures that are not solely anticipatory. Our primary interest, however, was to understand the inter-relationships between patterns of anticipatory fixations, age, and linguistic ability. To investigate this question, we operationally defined anticipatory looking as the mean proportion of time spent fixating on the Target object from the onset of the action word to the target word, i.e., over the portion of the sentence during which the necessary information to generate anticipatory looks was available. Since we are only interested in fixations that were generated after the onset of the action, fixations were excluded from analysis if their preceding saccade was initiated prior to action onset.

With these measurements, we first sought to determine if participants' fixations to the Target region significantly differed from fixations to other regions during the same period. Consequently, we conducted several planned comparisons to compare the difference in fixation proportion between the Target region and the (1) Agent-Related distractor, (2) the Action-Related distractor, and (3) the Unrelated distractor. If eye movements were driven by combinatorial integration of meanings from both the sentential agent and action, then we should expect to see that differences between looks to the Target and any other region should be significantly greater than zero. That is, if participants are indeed anticipating the upcoming target word before it is spoken, then we would expect participants to fixate to the Target image with greater magnitude than other objects, before the target itself is spoken. This is in fact what we found in every group, except for two: Children with lower sentence completion and lower vocabulary scores. These comparisons are summarized in Table 2.

Table 3 shows associations between online measures of mean proportion of anticipatory fixations to the Target object and offline measures of age and (age-normalized) linguistic ability. Even though Vocabulary and Sentence Completion was highly inter-correlated, r(96)=0.83, p<0.0001, only Vocabulary was significantly associated with the online measure of Anticipatory Fixation, r(96)=0.27, p=0.0086.

In order to further explore the relationship between the experimental and offline measures, we entered Age, Vocabulary and Sentence completion measures into a multiple regression model. Again, the only variable to explain significant variance in this model was that of Vocabulary, r(96)=.33, p<0.001. Neither Age, nor Sentence Completion scores explained significant variance in our experimental measure, either when they were entered either singly or in combination with other factors into the model. Since the Sentence Completion measure was highly inter-correlated with the Vocabulary measure and it failed to account for significant variance in task performance, we dropped this factor from subsequent analyses.

We further investigated the possibility that the relationship between Vocabulary and Sentence processing might potentially interact with Age, by carrying out an additional (2×2) ANOVA with factors of Age (Adult, Child) and a median split of age-normalized Vocabulary scores (High, Low). This analysis found a significant effect of Vocabulary, F(1,95)=11.23, p=0.0012, but not of Age, nor of Age × Vocabulary (Fs<1). To rule out that the general lack of Age effects might be driven by the inclusion of the adult participants in our analyses, we then conducted an identical ANOVA Age × Vocabulary analysis with only the children included. In this case, two Age groups were determined by a median split of Older and Younger children (younger range = 3;0–6; 3 years; older range = 6;5–10;0 years). Again, there was a main effect of Vocabulary, F(1,47)=6.84; p < 0.01, but not Age or Age × Vocabulary (Fs<1). This same pattern also holds when Age and Vocabulary are entered as continuous factors into a multiple regression model with children only: Vocabulary, F(1,47) = 9.35, p = 0.0038, Age and Age × Vocabulary (Fs<1). Similarly, a median-split of adults alone into higher and lower-scoring vocabulary groups yields significant effects of vocabulary, both for median-splits of age-normalized vocabulary scores, F(1,47)=3.99, p=0.05, and for raw PPVT, F(1,47)= 5.99, p=0.02. As continuous variables, adult raw PPVT scores significantly associate with anticipatory fixations, r(47)=0.30, p=0.04, but age-normalized PPVT scores do not.

Timecourse of fixations to the Action-related item—The timecourse Figures 2–5 suggest that participants in all groups generated additional looks to the Action-Related distractor at varying time points after hearing the verb. In order to quantify the timing of when these fixations diverged from that of looks to the distractor items, we conducted point-by-point t-tests to determine the time-window where the mean fixation proportions to the Action-Related distractor exceeded that that of the Unrelated distractor. As above, only time windows at which a minimum of 5 consecutive time points reached significance on this t-test measure are reported. This analysis revealed that children and adults in all examined groups fixated upon the Action-Related item in greater magnitude than the unrelated item, as reported in Table 4.

Discussion

In this investigation, we measured the relationships between anticipatory fixations during a simple spoken sentence comprehension task, age and linguistic ability. To our knowledge, this study is the first to show an association between vocabulary knowledge and incremental sentence interpretation in both adults and children. The study also replicates and extends a number of prior findings in the incremental sentence processing literature. As reported in previous studies (Altmann & Kamide, 1999; Kamide, et al., 2003), adults in this study launched anticipatory fixations to the target item starting at the action prior to the target. The timing with which these eye movements diverged from looks to other object regions was rapid in adults (1210 ms) – about 300 ms after the onset of the action. Given that it is generally considered to take about 200 ms to launch a saccade (cf. Altmann, 2011; Haith, 1993), the speed at which these fixations diverged indicates that adults were integrating information from the combined agent and action with remarkable speed.

We began by asking three questions. The first is whether the predictive behaviors found in children in simple looking tasks scale up to more complex language processing in which listeners must integrate cues over multiple words. The answer is an unequivocal *Yes*. Curiously, the anticipatory looking behaviors seem to be relatively larger than those seen by Kamideand colleagues (2003). We believe that much of this difference simply reflects methodological differences in the visual display and response demands between these two studies. Kamideet al. (2003) used a more naturalistic visual scene which included representations of both potential agents while we presented a simpler four-choice array in order reduce the distractibility of the scene for our younger participants. Additionally, while we asked our participants to select the item that represented the sentential object, Kamide and colleagues (2003) simply asked participants to attend to the visual display and sentences. As a result, we measured numerically larger fixation proportions to all items in the experiment, including the distractor. Even with these differences, the pattern of findings remains similar across the two studies. It is clear that these methodological adaptations were successful in our younger participants. The children understood and easily performed the task, since they made few response errors and generated anticipatory eye-movements with speeds that rivaled that of the adult participants. Yet it should be noted that some minor differences between children and adults did exist. The timecourse of looking to the Agent-Related and Target items early in the sentence did appear slightly different between child and adult groups. Since every item in our experimental design was completely balanced across conditions it is unlikely this was due to visual properties of our stimulus. However, it may represent a potential age-related strategy to look back at the Agent-Related before selecting the Target.

Our second question is how and whether such abilities vary across childhood. The (non-anticipatory) looking behaviors noted in Fernald, Pinto, Swingley, Weinberg, & McRoberts (1998) showed clear increases in speed between 15 and 24 months. We expected similar increases in this study. Although the children were older (3 to 10 years), the task was considerably more challenging. However, here we were surprised to find that age did not predict performance, considering children either alone or in comparison with adults. Strikingly, the children with the highest vocabulary levels performed nearly as quickly as adults with high vocabulary scores. This pattern is notable because high vocabulary children were both younger (average age of 6;5, range of 3;0–9;2), and had lower raw PPVT scores on this task than their college-student counterparts (mean PPVT score of high vocabulary children: 160, range 113–206 vs. high vocabulary adults 213, range 208–219), who are at least partially selected by having the requisite language ability to gain admission to university. One potential caveat of this finding however, concerns the nature of our stimuli. Since these sentences were spoken using child directed prosody, there is some possibility that adults, who are less familiar with this type of speech than children, may have been slowed to some extent on this task. Nonetheless, even when considering only child performance, effects of age were not as notable as that of vocabulary skill (corrected for age).

These results address our third question, which is what role one measure of linguistic ability – vocabulary skill – might play in predicting anticipatory looking skills. Vocabulary has been shown to strongly predict non-anticipatory looking in other tasks with very young children (Hurtado, Marchman, & Fernald, 2008). Similarly, other measures of linguistic ability, such as reading comprehension in school-aged children (Nation, et al., 2003) and self-rating of second language proficiency in college-aged adults (Chambers & Cooke, 2009) also seem to correlate with some aspects of predictive processing. In our tasks, we observed a complementary finding, where the participant's age-normalized score on a test of receptive vocabulary is a better predictor of anticipatory looking than age of the participant. That is, having a large vocabulary *for one's age* is important in this task. This result complements the earlier findings regarding vocabulary size per se, and contributes to the appreciation that the various relationships between age, vocabulary and speed of linguistic processing is somewhat complex, with the potential for multiple mediating factors. Since we fail to find age-related changes in processing on our task, our result is consistent with the interpretation that processing speed itself may contribute independently to vocabulary learning, rather than the other way around (Hurtado, Marchman, & Fernald, 2008). The relationship between vocabulary and online sentence comprehension is a topic that merits further study. It is also noteworthy that another measure of language ability, sentence completion, did not associate with performance on this task, even though sentence completion is itself highly correlated with vocabulary. This finding emphasizes the need to more finely determine what processing sub-skills and specific linguistic knowledge supports predictive processing in sentence comprehension.

Successful anticipatory performance on our task required not only an awareness of the semantic fit or association between the verb and the correct upcoming target, but also a more complex calculation of higher order contingences between the agent, action, and patient. For instance, in the sentence *"The pirate chases the ship,"* the associated visual display contains two objects that are potentially chaseable (SHIP and CAT), but only one that is likely to be chased by *the pirate*. The definition of likelihood here specifically invokes knowledge of real world events and situations. The present data indicate that, as seems true for adults (Bicknell, et al., 2010; Hald, et al., 2007; Kamide, et al., 2003; Matsuki, et al., 2011; Matsuki, Mcrae, Hare, & Elman, 2008; Metusalem et al., submitted) children age 3 to 10 years are able to rapidly integrate multiple cues during sentence processing and use real world knowledge of events and situations to guide their expectancies regarding upcoming referents.

Finally, we comment on the strategy that listeners appeared to be utilizing in this integrative process. The sentences in our design began with a cue (the agent) that potentially activated two visual items, the target and the agent-related distractor. As we noted above, one strategy, consistent with the COHORT model (Marslen-Wilson, 1987; Marslen-Wilson & Welsh, 1978) might be for listeners to use the subsequent cue (the action) to eliminate the agent-related distractor from this initial cohort, leaving active only the cohort. In this case, looks to the target should increase at mention of the action (which they did), but looks to all other distractors should decrease, including the initially activated agent distractor.

In fact, what appeared to happen is that listeners used a strategy more consistent with the TRACE model (McClelland & Elman, 1986). In TRACE, early cues activate an initial cohort of items that may be pruned by subsequent cues that are inconsistent with it. However, TRACE also allows subsequent cues to activate new items that are locally consistent with the new cues, even if they are inconsistent with the earlier cues. This might seem like a non-optimal strategy – why entertain hypotheses that one knows are not likely to be correct? – but it does allow for recovery under imperfect listening conditions in which the initial word onset was not processed correctly.

Indeed, this second strategy appears to best correspond to what listeners actually do when they identify words (Allopenna, Magnuson, & Tanenhaus, 1998), and seems to resemble what our participants did when processing sentences. Rather than only narrowing the range of targets they considered, listeners showed a willingness to predict targets that were locally consistent with the action, even though these targets were not expected given the already mentioned agent. Thus, looks to the action related target (e.g., CAT) increased at the verb when subjects heard *The pirate chased. . . .* In fact, there is increasing evidence in the adult sentence processing literature that locally coherent syntactic and semantic interpretations are temporarily activated (Kukona, et al., 2011; Tabor, et al., 2004). We suggest that this strategy may be advantageous when encountering unexpected outcomes during language comprehension. Rather than entirely discounting less expected possibilities, adults and children allow for the possibility that the unexpected may happen – although these less probable outcomes are weighted accordingly.

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References

1. Allopenna PD, Magnuson JS, Tanenhaus MK. Tracking the Time Course of Spoken Word Recognition Using Eye Movements: Evidence for Continuous Mapping Models. Journal of Memory and Language. 1998; 38(4):419.
2. Altmann GTM. Language can mediate eye movement control within 100 milliseconds, regardless of whether there is anything to move the eyes to. Acta Psychologica. 2011; 137(2):190–200. [PubMed: 20965479]
3. Altmann GTM, Kamide Y. Incremental interpretation at verbs: Restricting the domain of subsequent reference. Cognition. 1999; 73:247–264. [PubMed: 10585516]

4. Altmann GTM, Kamide Y. The real-time mediation of visual attention by language and world knowledge: Linking anticipatory (and other) eye movements to linguistic processing. Journal of Memory and Language. 2007; 57(4):502–518.
5. Altmann GTM, Mirkovic J. Incrementality and Prediction in Human Sentence Processing. Cognitive Science. 2009; 33(4):583–609. [PubMed: 20396405]
6. Anglin JM. Vocabulary development: A morphological analysis. Monographs of the Society for Research in Child Development. 1993; 58(10) Serial No: 238.
7. Arnold JE, Eisenband JG, Brown-Schmidt S, Trueswell JC. The rapid use of gender information: Evidence of the time course for pronoun resolution from eyetracking. Cognition. 2000; 76(1):B13–B26. [PubMed: 10822045]
8. Bates E, Goodman JC. On the Inseparability of Grammar and the Lexicon: Evidence from Acquisition, Aphasia and Real-Time Processing. Language and Cognitive Processes. 1997 Dec; v12(n5–6):507–584. 1997.
9. Bates, E.; Goodman, JC. On the emergence of grammar from the lexicon. In: MacWhinney, B., editor. The emergence of language. Mahwah, NJ: Lawrence Erlbaum; 1999. p. 29-79.
10. Beck, IL.; McKeown, MG. Conditions of vocabulary acquisition. In: Barr, R.; Kamil, M.; Mosenthal, P.; Pearson, PD., editors. Handbook of reading research. Vol. Vol. 2. New York: Longman; 1991. p. 789-814.
11. Bicknell K, Elman JL, Hare M, McRae K, Kutas M. Effects of event knowledge in processing verbal arguments. Journal of Memory and Language. 2010; 63(4):489–505. [PubMed: 21076629]
12. Boersma P. Praat, a system for doing phonetics by computer. Glot Internation. 2001; 5(9/10):341–345.
13. Bresnan, J. Lexical Functional Syntax. Malden, MA: Blackwell; 2001.
14. Carrow-Woolfolk, E. Comprehensive Assessment of Spoken Language. Circle Pines, MN: American Guidance Service; 1999.
15. Caselli C, Casadio P, Bates E. A Comparison of the Transition from First Words to Grammar in English and Italian. Journal of Child Language. 1999 Feb; v26(n1):69–111. 1999. [PubMed: 10217890]
16. Chambers CG, Cooke H. Lexical competition during second-language listening: Sentence context, but not proficiency, constrains interference from the native lexicon. Journal of Experimental Psychology: Learning, Memory, and Cognition; Journal of Experimental Psychology: Learning, Memory, and Cognition. 2009; 35(4):1029–1040.
17. Cooper RM. The control of eye fixation by the meaning of spoken language: A new methodology for the real-time investigation of speech perception, memory, and language processing. Cognitive Psychology. 1974; 6(1):84–107.
18. Cunningham AE, Stanovich KE. Early reading acquisition and its relation to reading experience and ability 10 years later. Dev Psychol. 1997; 33(6):934–945. [PubMed: 9383616]
19. Dahan D, Magnuson JS, Tanenhaus MK. Time Course of Frequency Effects in Spoken-Word Recognition: Evidence from Eye Movements. Cognitive Psychology. 2001; 42(4):317–367. [PubMed: 11368527]
20. Dale PS, Dionne G, Eley TC, Plomin R. Lexical and grammatical development: a behavioural genetic perspective. Journal of Child Language. 2000; 27(03):619–642. [PubMed: 11089341]
21. DeLong KA, Urbach TP, Kutas M. Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. Nature Neuroscience. 2005; 8(8):1117–1121.
22. Dunn, DM.; Dunn, LM. Peabody Picture Vocabulary Test. Minneapolis, MN: NCS Pearson, Inc.; 2007.
23. Ellis Weismer, S. Typical talkers, late talkers, and children with specific language impairment: A language endowment spectrum?. In: Paul, R., editor. The influence of developmental perspectives on research and practice in communication disorders: A festschrift for Robin S. Chapman. Mahwah, NJ: Lawrence Erlbaum Associates; 2007.
24. Elman J. Finding structure in time. Cognitive Science. 1990; 14(2):179–211.
25. Estes KG, Evans JL, Alibali MW, Saffran JR. Can Infants Map Meaning to Newly Segmented Words? Psychological Science. 2007; 18(3):254–260. [PubMed: 17444923]

26. Federmeier KD, Kutas M. A rose by any other name: Long-term memory structure and sentence processing. Journal of Memory and Language. 1999; 41(4):469–495.
27. Fenson L, Dale PS, Reznick JS, Bates E, Thal D. Variability in early communicative development. Monographs of the Society for Research in Child Development. 1994; 59 (Serial no, 242).
28. Fernald A, Perfors A, Marchman VA. Picking up speed in understanding: Speech processing efficiency and vocabulary growth across the 2nd year. Dev Psychol. 2006; 42(1):98–116. [PubMed: 16420121]
29. Fernald A, Pinto JP, Swingley D, Weinberg A, McRoberts GW. Rapid gains in speed of verbal processing by infants in the 2nd year. Psychological Science. 1998; 9(3)
30. Fernald A, Thorpe K, Marchman VA. Blue car, red car: Developing efficiency in online interpretation of adjectiveâ€“noun phrases. Cognitive Psychology. 2010; 60(3):190–217. [PubMed: 20189552]
31. Fernald, A.; Zangl, R.; Portillo, AL.; Marchman, V. Looking while listening: Using eye movements to monitor spoken language comprehension by infants and young children. In: Sekerina, I.; Fernandez, E.; Clahsen, H., editors. Language Processing in Children. Amsterdam: Benjamins; 2008.
32. Friedrich M, Friederici AD. N400-like Semantic Incongruity Effect in 19-Month-Olds: Processing Known Words in Picture Contexts. J. Cogn. Neurosci. 2004; 16(8):1465–1477. [PubMed: 15509391]
33. Friedrich M, Friederici AD. Lexical priming and semantic integration reflected in the event-related potential of 14-month-olds. Neuroreport. 2005; 16(6):653–656. [PubMed: 15812327]
34. Gathercole SE, Baddeley AD. Evaluation of the role of phonological STM in the development of vocabulary in children: A longitudinal study. Journal of Memory and Language. 1989; 28(2):200–213.
35. Graves, MF. Vocabulary learning and instruction. In: Rothkopf, EZ., editor. Review of Research in Education. 1986. p. 49-89.13.
36. Haith, MM. Granrud, C. Visual Perception and Cognition in Infancy. Hillsdale, NJ: Lawrence Erlbaum Associates; 1993. Future-oriented processes in infancy: The case of visual expectations.
37. Hald LA, Steenbeek-Planting EG, Hagoort P. The interaction of discourse context and world knowledge in online sentence comprehension. Evidence from the N400. Brain Research. 2007; 1146(0):210–218. [PubMed: 17433893]
38. Hare M, Jones M, Thomson C, Kelly S, McRae K. Activating event knowledge. Cognition. 2009; 111(2):151–167. [PubMed: 19298961]
39. Hockett CD. The Origin of Speech. Scientific American. 1960; 203(3):88–96. [PubMed: 13683472]
40. Hurtado N, Marchman VA, Fernald A. Does input influence uptake? Links between maternal talk, processing speed and vocabulary size in Spanish-learning children. Developmental Science. 2008; 11(6):F31–F39. [PubMed: 19046145]
41. Kamide Y, Altmann GTM, Haywood S. The time-course of prediction in incremental sentence processing: Evidence from anticipatory eye movements. Journal of Memory & Language. 2003; 49:133–156.
42. Kidd E, Bavin EL. Lexical and referential cues to sentence interpretation: an investigation of children's interpretations of ambiguous sentences. Journal of Child Language. 2005; 32(04):855–876. [PubMed: 16429714]
43. Kukona A, Fang S-Y, Aicher KA, Chen H, Magnuson JS. The time course of anticipatory constraint integration. Cognition. 2011; 119(1):23–42. [PubMed: 21237450]
44. Kuperberg GR. Neural mechanisms of language comprehension: Challenges to syntax. Brain Research. 2007; 1146(0):23–49. [PubMed: 17400197]
45. Lew-Williams C, Fernald A. Real-time processing of gender-marked articles by native and non-native Spanish speakers. Journal of Memory and Language. 2010; 63(4):447–464. [PubMed: 21076648]
46. Maital SL, Dromi E, Abraham S, Bornstein MH. The Hebrew Communicative Development Inventory: language specific properties and cross-linguistic generalizations. Journal of Child Language. 2000; 27(01):43–67. [PubMed: 10740967]

47. Marchman VA, Bates E. Continuity in lexical and morphological development: A test of the critical mass hypothesis. Journal of Child Language. 1994; 21(2):339–366. [PubMed: 7929685]

48. Marchman VA, Fernald A. Speed of word recognition and vocabulary knowledge in infancy predict cognitive and language outcomes in later childhood. Dev Sci. 2008; 11(3):F9–F16. [PubMed: 18466367]

49. Marchman VA, Martínez-Sussmann C, Dale PS. The language-specific nature of grammatical development: evidence from bilingual language learners. Developmental Science. 2004; 7(2):212–224. [PubMed: 15320381]

50. Marslen-Wilson WD. Functional parallelism in spoken word-recognition. Cognition. 1987; 25(1–2):71–102. [PubMed: 3581730]

51. Marslen-Wilson WD, Welsh A. Processing interactions and lexical access during word recognition in continuous speech. Cognitive Psychology. 1978; 10(1):29–63.

52. Martino NL, Hoffman PR. An investigation of reading and language abilities of college freshmen. Journal of Research in Reading. 2002; 25(3):310–318.

53. Matsuki K, Chow T, Hare M, Elman JL, Scheepers C, McRae K. Event-Based Plausibility Immediately Influences On-Line Language Comprehension. Journal of Experimental Psychology-Learning Memory and Cognition. 2011; 37(4):913–934.

54. Matsuki K, Mcrae K, Hare M, Elman J. On-line dynamic combination of concepts during language comprehension. Canadian Journal of Experimental Psychology-Revue Canadienne De Psychologie Experimentale. 2008; 62(4):282–282.

55. McClelland JL, Elman JL. The TRACE model of speech perception. Cognitive Psychology. 1986; 18(1):1–86. [PubMed: 3753912]

56. Metsala JL. The development of phonemic awareness in reading-disabled children. Applied Psycholinguistics. 1999; 20(01):149–158.

57. Metusalem, R.; Kutas, M.; Hare, M.; McRae, K.; Elman, JL. Generalized event knowledge activated during on-line language comprehension. In: Ohlsson, S.; Catrambone, R., editors. Proceedings of the Thirty-Second Annual Meeting of the Cognitive Science Society. Austin, TX: Cognitive Science Society; 2010. p. 1058-1063.

58. Metusalem R, Kutas M, Urbach T, Hare M, McRae K, Elman J. Generalized event knowledge activation during online sentence comprehension. (submitted).

59. Mills DL, Coffey-Corina S, Neville HJ. Language comprehension and cerebral specialization from 13 to 20 months. Developmental Neuropsychology. 1997; 13(3):397–445.

60. Misyak JB, Christiansen MH, Bruce Tomblin J. Sequential Expectations: The Role of Prediction-Based Learning in Language. Topics in Cognitive Science. 2010; 2(1):138–153.

61. Moyle MJ, Ellis Weismer S, Evans JL, Lindstrom MJ. Longitudinal Relationships Between Lexical and Grammatical Development in Typical and Late-Talking Children. J Speech Lang Hear Res. 2007; 50(2):508–528. [PubMed: 17463244]

62. Nation, K. Reading comprehension and vocabulary: Whats the connection?. In: Wagner, RK.; Schatschneider, C.; Phythian-Sence, C., editors. Beyond decoding: the behavioral and biological foundations of reading comprehension. New York, NY: The Guilford Press; 2009. p. 176-194.

63. Nation K, Marshall CM, Altmann GTM. Investigating individual differences in children's real-time sentence comprehension using language-mediated eye movements. Journal of Experimental Child Psychology. 2003; 86(4):314–329. [PubMed: 14623215]

64. Norris D. Shortlist: a connectionist model of continuous speech recognition. Cognition. 1994; 52(3):189–234.

65. Paul R. Clinical Implications of the Natural History of Slow Expressive Language Development. Am J Speech Lang Pathol. 1996; 5(2):5–21.

66. Pollard, C.; Sag, IA. Head-Driven Phrase Structure Grammar. Chicago: University of Chicago Press; 1994.

67. Rescorla L. Do late talking toddlers turn out to have languages and reading difficulties a decade later? Annals of Dyslexia. 2000; 50:87–102.

68. Research, S. SR Research Experiment Builder Mississauga. Ontario, Canada: SR Research Ltd.; 2011.

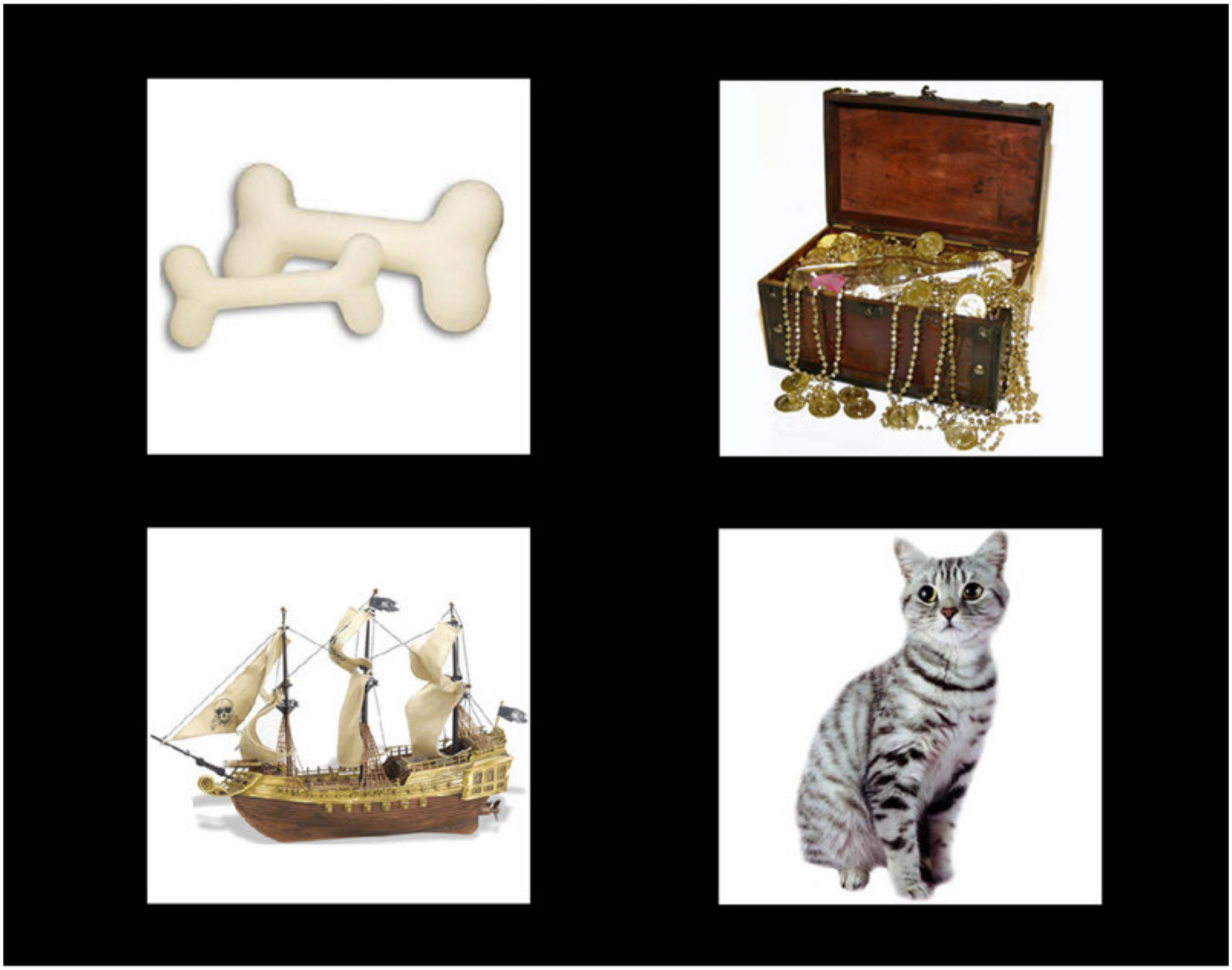
69. Rodriguez, P.; Wiles, J.; Elman, JL. A recurrent neural network that learns to count. Vol. Vol. 11. London, ROYAUME-UNI: Taylor & Francis; 1999.
70. Saffran JR, Aslin RN, Newport EL. Statistical Learning by 8-Month-Old Infants. Science. 1996; 274(5294):1926–1928. [PubMed: 8943209]
71. Salverda AP, Dahan D, McQueen JM. The role of prosodic boundaries in the resolution of lexical embedding in speech comprehension. Cognition. 2003; 90(1):51–89. [PubMed: 14597270]
72. Sedivy JC, Tanenhaus MK, Chambers CG, Carlson GN. Achieving incremental semantic interpretation through contextual representation. Cognition. 1999; 71(2):109–147. [PubMed: 10444906]
73. Snedeker J, Trueswell J. The developing constraints on parsing decisions: The role of lexical-biases and referential scenes in child and adult sentence processing. Cognitive Psychology. 2004; 49(3):238–299. [PubMed: 15342261]
74. Stahl, SA.; Nagy, ME. Teaching word meanings. Mahwah, NJ: Lawrence Erlbaum; 2006.
75. Steedman, M.; Baldridge, J. Combinatory Categorial Grammar. In: Brown, K., editor. Encyclopedia of Language and Linguistics. Vol. Vol. 2. Oxford: Elsevier; 2006. p. 610-622.
76. Tabor W, Galantucci B, Richardson D. Effects of merely local syntactic coherence on sentence processing. Journal Of Memory And Language. 2004; 50(4):355–370.
77. Tanenhaus MK, Magnuson JS, Dahan D, Chambers C. Eye Movements and Lexical Access in Spoken-Language Comprehension: Evaluating a Linking Hypothesis between Fixations and Linguistic Processing. Journal of Psycholinguistic Research. 2000; 29(6):557–580. [PubMed: 11196063]
78. Tanenhaus MK, Spivey-Knowlton MJ, Eberhard KM, Sedivy JC. Integration of visual and linguistic information in spoken language comprehension. Science. 1995; 268(5217)
79. Thordardottir ET, Ellis Weismer S, Evans JL. Continuity in lexical and morphological development in Icelandic and English-speaking 2-year-olds. First Language; First Language. 2002; 22(64, Pt1):3–28.
80. Travis KE, Leonard MK, Brown TT, Hagler DJ, Curran M, Dale AM, et al. Spatiotemporal Neural Dynamics of Word Understanding in 12- to 18-Month-Old-Infants. Cerebral Cortex. 2011
81. Trueswell JC, Sekerina I, Hill NM, Logrip ML. The kindergarten-path effect: studying online sentence processing in young children. Cognition. 1999; 73(2):89–134. [PubMed: 10580160]
82. Trueswell JC, Tanenhaus MK, Kello C. Verb-specific constraints in sentence processing: Separating effects of lexical preference from garden-paths. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1993; 19(3):528–553.
83. VanBerkum JJA, Brown CM, Zwitserlood P, Kooijman V, Hagoort P. Anticipating Upcoming Words in Discourse: Evidence From ERPs and Reading Times. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2005; 31(3):443–467.
84. Verhaeghen P. Aging and Vocabulary Scores: A Meta-Analysis. Psychology and Aging. 2003; 18(2):332–339. [PubMed: 12825780]
85. Whipple, G., editor. The twenty-fourth yearbook of the National Society for the Study of Education: Report of the National Committee on Reading. Bloomington, IL: Public School Publishing; 1925.
86. White TG, Graves MF, Slater WH. Growth of reading vocabulary in diverse elementary schools: Decoding and word meaning. Journal of Educational Psychology. 1990; 82(2):281–290.
87. Whitehurst GJ, Fischel JE. Early developmental language delay: What, if anything, should a clinician do about it? Journal of Child Psychology and Psychiatry. 1994; 35:613–648. [PubMed: 8040218]
88. Wicha NYY, Moreno EM, Kutas M. Anticipating Words and Their Gender: An Event-related Brain Potential Study of Semantic Integration, Gender Expectancy, and Gender Agreement in Spanish Sentence Reading. Journal of Cognitive Neuroscience. 2004; 16(7):1272–1288. [PubMed: 15453979]
89. Zechmeister EB, Chronis AM, Cull WL, D'Anna CA, Healy NA. Growth of a functionally important lexicon. Journal of Reading Behavior. 1995; 27(2):201–212.

Appendix A: List of the 32 sentences designed for the study

The fireman rides the truck.
The girl rides the bike.
The fireman tastes the hamburger.
The girl tastes the candy.
The shark swims in the ocean.
The boy swims in the pool.
The shark catches the fish.
The boy catches the ball.
The pirate hides the treasure.
The dog hides the bones.
The pirate chases the ship.
The dog chases the cat.
The baby drinks the milk.
The woman drinks the water.
The baby wears the diaper.
The woman wears the dress.
The cat catches the bird.
The frog catches the fly.
The cat jumps into the couch.
The frog jumps into the pond.
The monkey jumps through the trees.
The dolphin jumps through the waves.
The monkey eats the banana.
The dolphin eats the fish.
The baby eats the cookie.
The cow eats the grass.
The baby sleeps in the crib.
The cow sleeps in the barn.
The boy flies the kite.
The pilot flies the airplane.
The boy wears the t-shirt.
The pilot wears the helmet.

Highlights

- Anticipatory sentence interpretation is examined in children (3–10 years) and adults.
- Both groups rapidly combined agent and action cues to predict sentence final objects.
- Vocabulary but not age was associated with anticipatory fixations in both groups.
- Adults and children used similar sentence interpretation strategies.
- Results suggest important relationships between vocabulary and predictive processing.



Spoken sentence					**Target**	**Agent Related**	**Action Related**	**Unrelated**
The	*pirate*	*hides*	*the*	*treasure.*	TREASURE	SHIP	BONES	CAT
The	*pirate*	*chases*	*the*	*ship.*	SHIP	TREASURE	CAT	BONES
The	*dog*	*hides*	*the*	*bones*	BONES	CAT	TREASURE	SHIP
The	*dog*	*chases*	*the*	*cat*	CAT	BONES	SHIP	TREASURE
Art1	Agent	Action	Art2	Target				

Figure 1.

Illustration of stimuli and conditions in the experimental task.

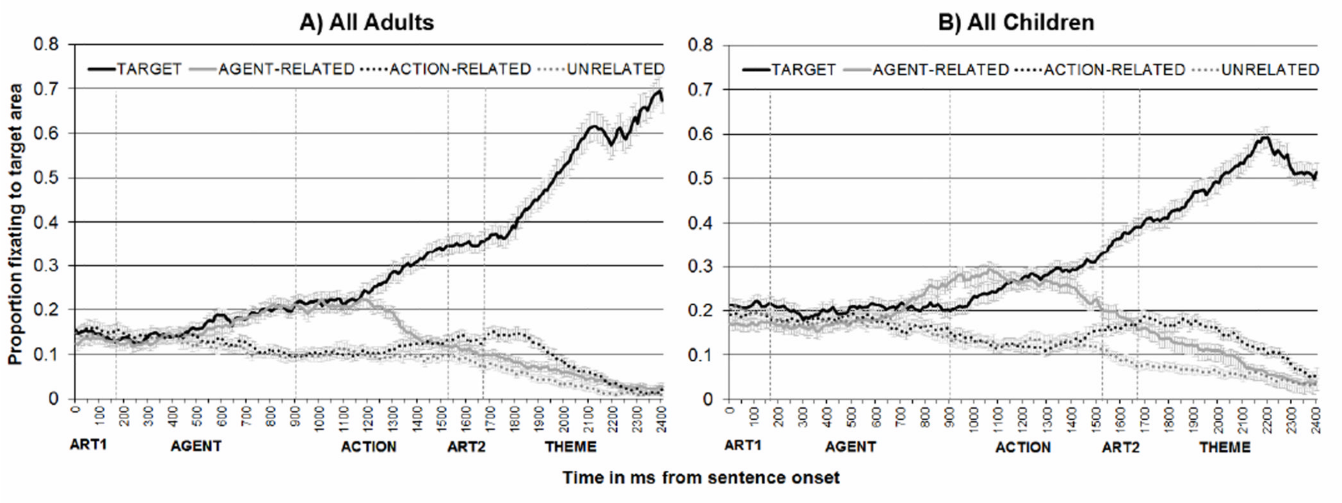


Figure 2.

Timecourse of fixating to target and competitors interest areas (with SE bars) during the sentence in all adults (1a) and all children (1b) plotted in 10ms time-bins.

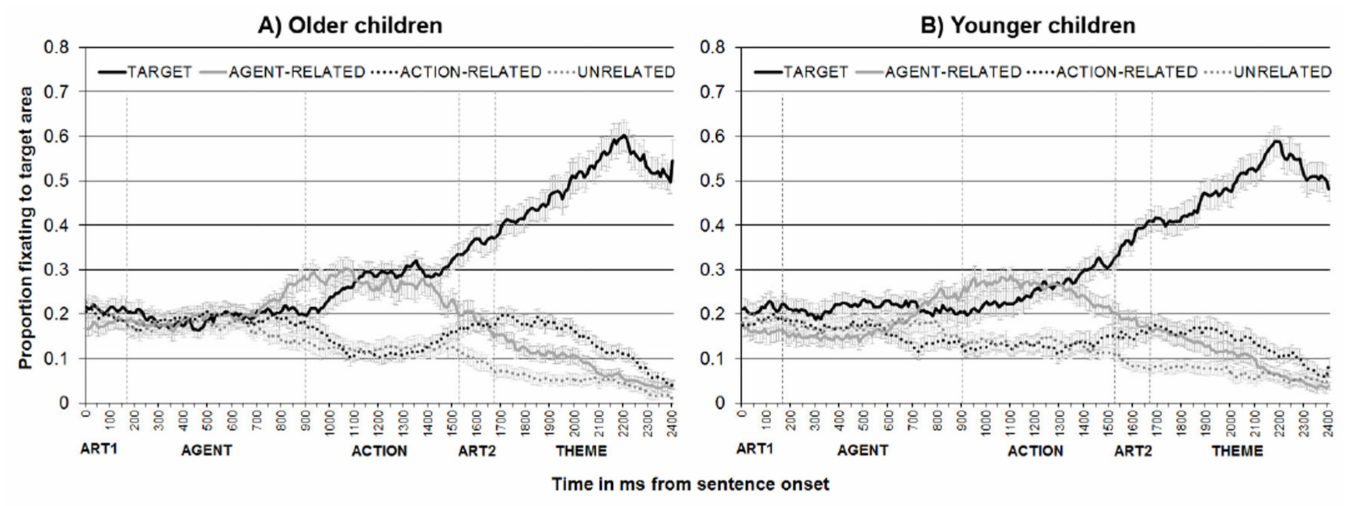


Figure 3.

Proportion of time fixating to each interest area in 10 ms time bins (with SE bars) from sentence onset to sentence offset, for (3a) older and (3b) younger children.

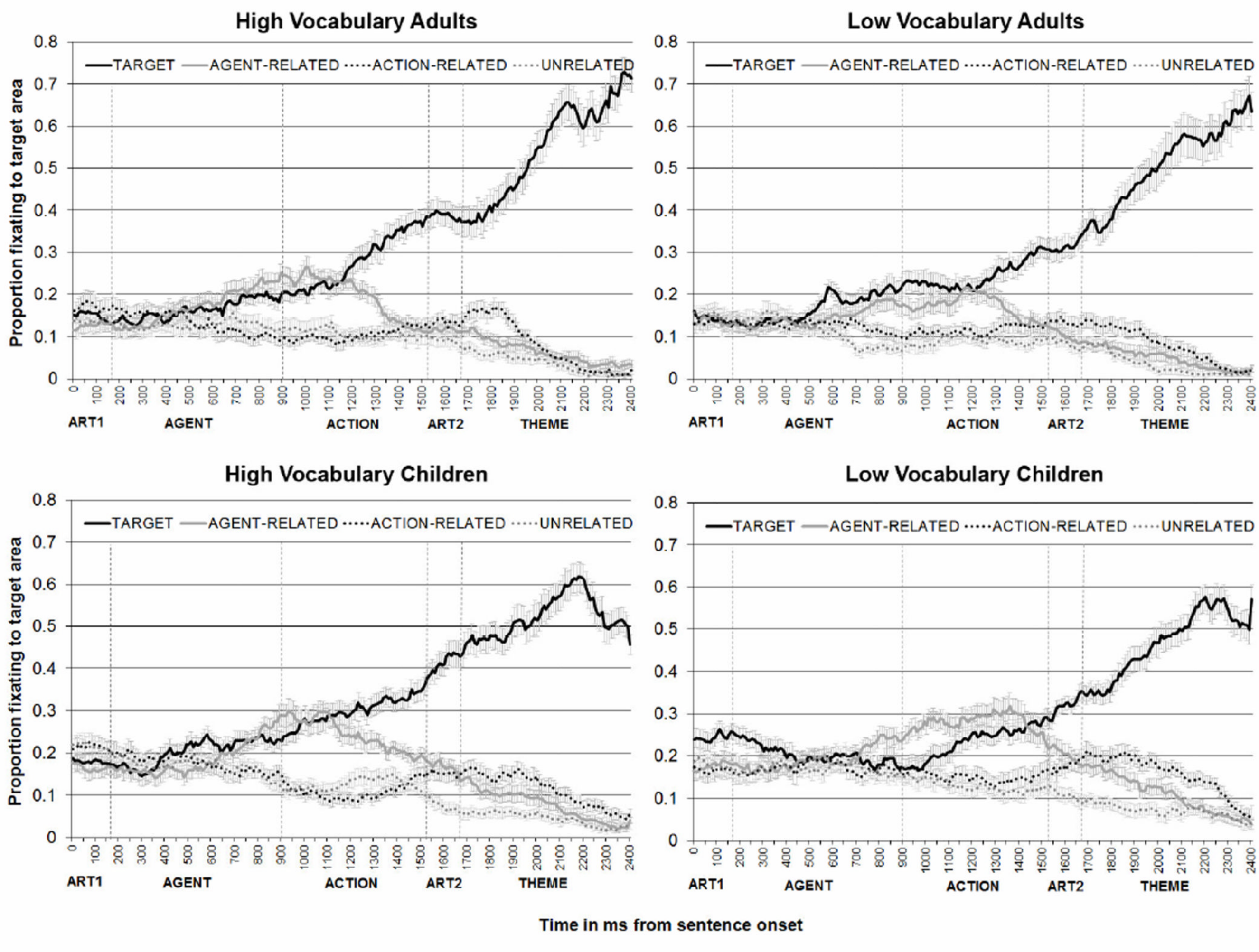


Figure 4.

Timecourse of fixations to target and distractor interest areas (with SE bars) during the sentence plotted in 10ms time-bins for adults and children in high and low vocabulary median split groups.

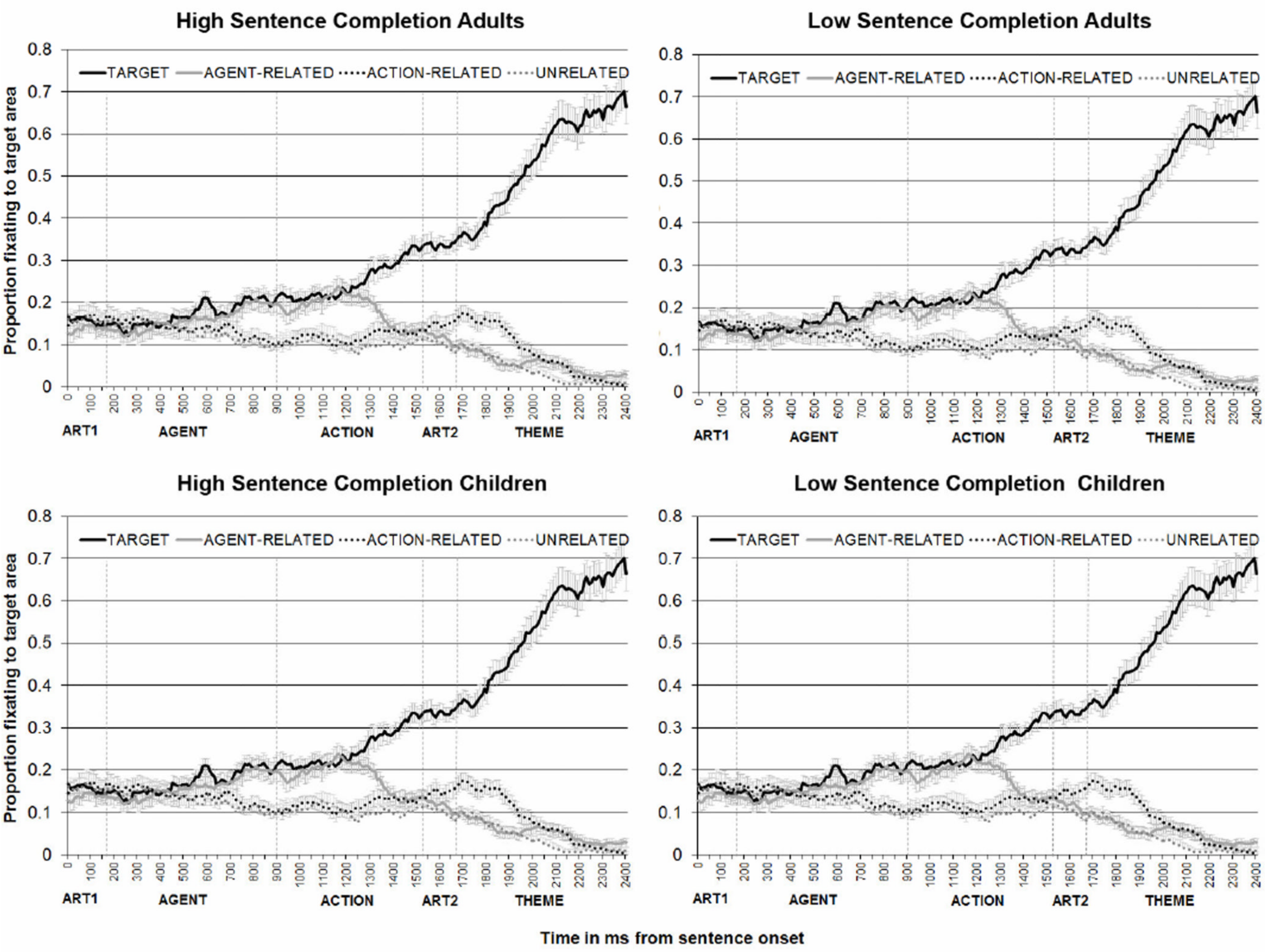


Figure 5.

Timecourse of fixations to target and distractor interest areas (with SE bars) during the sentence plotted in 10ms time-bins for adults and children in high and low sentence completion median split groups.

Table 1

Demographics of children in all median split groups

Group	**Age Range**	**Mean Age**	**Sex**
Older Children	6;5–10;0	8;0 (2.5)	13 F, 11 M
Younger Children	3;0–6;3	4;3 (2.9)	9 F, 15 M
High Vocabulary	3;0–9;2	6;5 (4.7)	12 F, 12 M
Low Vocabulary	3;0–10;0	5;11 (6.0)	10 F, 14 M
High Sent. Completion	3;0–9;2	6;4 (4.6)	13 F, 11 M
Low Sent. Completion	3;0–10;0	5;11 (6.1)	9 F, 15 M

Note: Std. Errors are reported in parentheses.

Table 2

T-scores for difference between fixations proportions in the anticipatory time window to the Target image minus Distractors.

	Target -Agent-Related	**Target -Action-Related**	**Target -Unrelated**
All Adults	7.14[***]	8.34[***]	8.74[***]
High Voc Adult	6.44[***]	7.38[***]	6.66[***]
Low Voc Adults	3.81[**]	4.68[***]	6.00[***]
High SC adults	5.64[***]	6.53[***]	5.87[***]
Low SC adults	4.55[***]	5.26[***]	7.09[***]
All Children	2.50[**]	7.5[***]	8.3[***]
Older Children	1.90[**]	6.72[***]	7.05[***]
Younger Children	1.59[#]	4.24[**]	4.85[***]
High Voc Children	5.00[***]	9.80[***]	6.90[***]
Low Voc Children	−0.552	3.06[*]	5.05[***]
High SC children	4.05[**]	9.99[***]	6.81[***]
Low SC children	0.190	3.09[**]	5.01[***]

[*] - $p < 0.01$,

[**] - $p < 0.001$,

[***] - $p< 0.0001$.

[#] - $p =0.062$

Table 3

Pearson correlation coefficients (r) between online measures of mean proportion of anticipatory fixations to the Target object, age and offline measures of language ability, n=96 (48 children + 48 adults)

	Anticipatory Fixations	**Vocabulary**	**Sentence Completion**	**Age**
Anticipatory Fixations	--	0.27*	0.17	.012
Vocabulary	0.27*	--	.83**	0.004
Sentence Completion	0.17	.83**	--	−0.0001
Age	.012	0.004	−0.0001	--

* - $p < 0.01$,

** - $p < 0.0001$

Table 4

Summary of fixation divergence times for Target and Action-Related items.

Comparison:	**Target vs. Agent-Related**	**Action-Related vs. Unrelated**
All Adults	1220ms	1430–1490ms, 1520–2240ms
All Children	1420ms	1480–2370ms
Older Children	1410ms	1530–2400ms
Younger Children	1460ms	1440–2280ms
High Vocabulary Adults	1210ms	1650–1990ms
Low Vocabulary Adults	1310ms	1310–1470ms, 1510–2250ms
High Vocabulary Children	1220ms	1510–2350ms
Low Vocabulary Children	1520ms	1570–2290ms
High Sentence Completion Adults	1220ms	1510–2050ms, 2150–2230ms
Low Sentence Completion Adults	1300ms	1620–2170ms
High Sentence Completion Children	1320ms	1490–2340ms
Low Sentence Completion Children	1520ms	1570–2290ms