Children's Online Processing of Complex Sentences: New Evidence from a New Technique

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Abstract

A lack of straightforward, child-appropriate methodologies has hindered the study of on-line syntactic processing in young children. Here, we exploited the continuous and non-ballistic properties of computer mouse movements, identified by recording streaming *x, y* coordinates, to test how young children integrate multiple sources of information on-line in order to extract meaning. Participants heard structurally ambiguous sentences while viewing scenes with properties that did or did not support the difficult noun phrase modifier interpretation. As previously reported, children have difficulty accessing and utilizing the scene-based context cue. This difficulty, however, was significantly more pronounced in children with less language exposure.

Keywords: Sentence Processing; Language Comprehension; Mouse-Tracking; Language Development; Multiple Cues

Over the past 15-20 years, a large amount of evidence has accrued in support of the notion that when a sentence is heard or read, the adult language comprehension system rapidly accesses many different linguistic and/or non-linguistic information sources to extract structure and meaning from the signal (Altmann & Steedman, 1988; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Snedeker & Trueswell, 2004). Until recently, however, a lack of child-appropriate behavioral techniques has hindered the study of young children's on-line syntactic processing and development. Here, we consider the degree to which multiple cues facilitate the comprehension of syntactically ambiguous sentences in children and adults, outline a new technique to facilitate the study of on-line language processing in young children, and present new data from that technique to support previous findings in children's sentence processing.

On-line language comprehension is commonly studied by presenting syntactically ambiguous sentences and then examining the sources of information that influence the manner in which they are initially interpreted.

1a) Put the apple on the towel in the box.

1b) Put the apple that's on the towel in the box.

In example (1), the prepositional phrase (PP) *on the towel* creates a syntactic ambiguity in that it can be initially interpreted as a destination (or Goal) for the referring expression *the apple*, thus attaching to the verb phrase (VP-Attachment), or alternatively, could be interpreted as a modifier of the noun phrase (NP), such as *Put [the apple on the towel] in the box* (NP-attachment).

The influence of both referential context and the lexical-bias of the verb are two information sources that have been shown to interact in determining how adults initially attach the ambiguous PP. When ambiguous sentences like (1a) are heard in the presence of visual scenes where only one referent is present (an apple already on a towel), along with an incorrect destination (an empty towel), and a correct destination (a box), adults often look to the incorrect destination until the second disambiguating PP is heard, at which time eye-movements tend to be re-directed to the correct destination (Tanenhaus et al., 1995; Trueswell, Sekerina, Hill, & Logrip, 1999). Looks to the incorrect destination are indicative of "garden-pathing," initially incorrectly attaching the PP to the verb phrase, because they do not occur when the instruction is unambiguous (1b).

The looking patterns are, however, markedly different when the visual context contains two possible referents (say, an apple on a towel and another apple on a napkin). When hearing an ambiguous sentence like (1a) in a "two-referent" visual context, adults tend to look at the correct referent (the apple on the towel) and move it to the correct destination with few looks to the incorrect destination. In accordance with various instantiations of referential theory (Altmann & Steedman, 1988; Spivey & Tanenhaus, 1998), when two possible referents are present, an expectation is created that the two similar entities will be discriminated, thereby forcing a modifier interpretation of the initial PP (NP-attachment).

This context effect is modulated, however, by lexical biases, such as the frequency with which the verb (like *Put*) takes a prepositional object (such as *on the towel*) in naturally occurring language. When the lexical bias of a verb strongly supports VP-attachment, adults strongly prefer the VP-attached interpretation of the PP (Britt, 1994; Snedeker & Trueswell, 2004), especially when the context also supports VP-attachement (when only one referent is present). If, however, a verb often does not take a prepositional object at all (such as *drop*), adults favor NP-attachment (Snedeker & Trueswell, 2004), and this preference is especially strong when the context also supports NP-attachment.

By examining young children's eye-movement patterns in similar scene-based experimental paradigms, Snedeker & Trueswell (2004) revealed that, like adults, five-year-old children tend to attach the ambiguous PP in sentences like

(1a) to the VP or the NP in accordance with the lexical-bias of the verb. Unlike adults, however, the scene-based referential context does not interact with the lexical-bias of the verb in determining which interpretation is initially entertained. That is, although children showed remarkable sensitivity to the biases of the verbs, context could not, in an additive sense, further facilitate children's initial attachment preference (although it did exert slight effects in later processing stages).

When comparing children to adults, then, Snedeker and Trueswell argued that children could access multiple sources of information from very early on but that children prioritize the amount of influence from each source based on the overall reliability of that information source in typical input. Children rely heavily on the lexical-biases of the verbs because they are extremely reliable across the input. When a PP follows *Put* in child-directed speech, for example, it almost always denotes a destination for the "putting" action. Salient cues from visual context, however, are more complex and less frequent, and as such, less easy to track and learn. As a result, context is less influential in children because it takes a longer time to learn.

Such an argument is based strongly on experience with the input. Indeed, Snedeker and Trueswell found that off-line attachment preferences entailed by specific verbs aligned very well with the behavior of those verbs in naturally occurring child-directed speech. They concluded that lexical-bias was a strong cue for young children but that visual context doesn't become a reliable constraint on parsing until slightly later in life.

Purpose

Recent research demonstrates that continuous nonlinear trajectories recorded from the streaming *x, y* coordinates of computer-mouse movements can serve as an informative indicator of the cognitive processes underlying spoken word recognition (Spivey, Grosjean, & Knoblich, 2005), categorization (Dale, Kehoe, & Spivey, in press), and adult syntactic processing (Farmer, Cargill, & Spivey, in press). Unlike saccadic eye movements, mouse movements are generally smooth and continuous, and can curve substantially mid-flight. Additionally, although eye-movement data afford approximately 2-4 data points (saccades) per second, "mouse-tracking" yields somewhere between 30-60 data points per second, depending on the sampling rate of the software used. These properties of tracked mouse-movements provide crucial benefits in that they allow a fine-grained and graded response pattern to emerge within an individual trial.

Although evidence exists that children can click a computer mouse at 3.5 years, on average, and that the onset of autonomous computer use is approximately 3.7 years (Calvert, Rideout, Woolard, Barr, and Strouse, 2005), the degree to which this cheap, portable, and accessible technique can be used to study complex cognitive phenomena in young children remains to be seen. Here, we exploit the continuous nature of mouse-movement trajectories, in relation to the visual-world paradigm (Tanenhaus et al., 1995), in order to determine whether the relatively fragile effect of context would emerge when examining the very sensitive and fine-grained properties of mouse-movement trajectories.

In the present research, children moved objects around a natural scene in response to ambiguous (1a) and unambiguous spoken instructions (1b). To hold the lexical-bias variable constant, sentences contained only the verb *Put*, which is strongly biased toward VP attachment. In the one-referent context, we predicted significant curvature toward the ultimately incorrect destination for ambiguous sentences, signaling some consideration of VP-attachment. In the two-referent context, we tested competing hypotheses. If the mouse-movement data can be expected to provide the same result as the eye-movement data, we would predict significant ambiguous-sentence trajectory curvature toward the incorrect destination. If, however, children can in fact use context to reduce the degree to which they consider the VP-attachment alternative, but eye-movement data were not sensitive enough to detect a subtle context effect in children, we would predict no significant divergence between the ambiguous- and unambiguous-sentence conditions in the two-referent context.

Additionally, although Snedeker and Trueswell (2004) made the claim that adults, given more exposure to more reliable input (especially in relation to context), were more able to use context than children, it might be the case that other developmental changes, like an increase in working memory, cognitive control, attention, etc., better account for differences in adults' use of context. Therefore, to begin to investigate the role of individual differences in language experience in sentence processing, we also included a measure of language experience, vocabulary, with child participants. If exposure to the input helps drive the comprehension system toward adult-like behavior, children with more language experience should have a more adult-like use of context than children with less language experience. In this experiment, the context cue should not completely override the garden-path effect, because *put* has a strong verb-based bias toward VP attached (and against the ultimately correct modifier attachment). However, in the two-referent condition, we predict that low language-experience children will exhibit a more robust garden-path effect than high-experience children.

Method

Participants Forty-three participants, 19 females and 24 males, between the ages of 56 and 70 months-old (M=63.38 months) participated in this experiment.

Materials and Procedure Sixteen experimental items, along with 80 filler sentences, were adapted from Spivey et al. (2002) and digitally recorded. Each item was made "child-friendly" by substituting potentially unfamiliar objects with objects included in the MacArthur-Bates Communicative Development Inventory, a widely used parental-report based collection of productive vocabulary for children up to 30 months (Fenson et al., 1994). Ambiguous (1a) and unambiguous instructions (1b) that corresponded to each of 16 experimental scenes were recorded (see Spivey et al., 2002 for details). Each of the visual scenes corresponding to the 16 experimental items was varied to produce a one-referent condition and a two-referent condition. The one-referent visual context (Figure 1, top) contained a target referent (e.g., an apple on a towel), an incorrect destination (e.g., a second towel), the correct destination (e.g., a box), and a distracter object (e.g., a flower). In the two-referent context (Figure 1, bottom), all items were the same except that the distracter was replaced with a second possible referent (such as an apple on a napkin). Sixteen distracter scenes, designed to accompany filler sentences, were constructed using different combinations of the objects from the experimental trials and from a set of new and easily recognizable objects.

Spoken instructions were recorded using a Mac-based speech synthesizer program. The experimental screen with the target referent, distracter or second referent, and the incorrect and correct destinations appeared on the monitor. For each scene, at the beginning of the sound-file participants first heard "Place the arrow at the center of the cross." Once the child moved the cursor to the center of the cross, the mouse was repositioned to the center of a small sticker on the table, so that the cursor always started in the same place for each trial. Sound-files accompanying experimental scenes always played the experimental sentence first, followed by two additional filler instructions. Thus, for experimental items, participants viewed the appropriate scene while hearing, for example:

1) Place the cursor at the center of the cross.
2) Put the apple on the towel in the box (experimental trial).
3) Now put the apple beside the flower (filler sentence).
4) Now put the flower in the box (filler sentence).

16 additional filler scenes were also created, and participants heard three scene-appropriate unambiguous filler instructions accompany these. In all cases, six seconds separated the offset of one sentence from the onset of the next within each trial. Between trials, children saw a large yellow star centered on the screen and heard the enthusiastically spoken instruction "Click on the star to go on!" This step was included to keep the child motivated and to provide a natural break in the experiment. All instructions were recorded in age-appropriate child-directed speech by a female adult.

In both the one- and two-referent conditions, the target referent always appeared in the top left corner of the screen, the incorrect destination always appeared in the top right corner, and the correct destination was always located at the bottom right corner (as in Figure 1). The bottom left corner of the screen showed either the distracter object in the one-referent trials or the second referent in the two-referent trials. Filler sentences were constructed to prevent participants from detecting the regularity created by the object placements in the experimental trials. In addition to the movement used in the experimental instructions, eleven distinct movements were possible in the visual scene across trials, and an approximately equal number of filler sentences (either eight or ten) were assigned to each of these movements. Therefore, ten sentences required an object in the upper left-hand corner to be moved to the upper right corner of the display, eight sentences required an object in the upper left-hand corner to be moved to the bottom left-hand corner, and so on.

In each scene, participants saw four to six color images, depending on the instructions. Images were constructed from pictures of real objects taken by a digital camera and edited in Adobe Photoshop. Visual stimuli subtended an average of 5.96 X 4.35 degrees of visual angle, and were 14.38 degrees diagonally from the central cross. Mouse movements were recorded at an average sampling rate of 40 Hz.

The experimental items were counterbalanced across four presentation lists. Each list contained four instances of each possible condition, but only one version of each sentence frame and corresponding visual context. Participants were randomly assigned to one of the four presentation lists, and the presentation order was randomized for each participant. Three practice items were incorporated into the beginning of each list, and participants were randomly assigned to one of the four presentation lists.

Each child also completed the Peabody Picture Vocabulary Test—Third Edition (PPVT-III), a widely-used and reliable test of receptive vocabulary. Participants heard a spoken word and were asked to choose the correct referent from a display including four pictures. Half of the subjects received the PPVT before the computer portion of the experiment and the other half of the subjects received it after. Additionally, parents completed a form, providing information about the child's computer use and their demographic information. The session lasted approximately 30 minutes.

Results

Data Screening and Coding Mouse movements were recorded during the grab-click, transferal, and drop-click of the referent object in the experimental trials. As a result of the large number of possible trajectory shapes, the *x,y* coordinates for each trajectory from each experimental trial were plotted in order to detect the presence of errors or otherwise aberrant movements. A trajectory was considered valid and submitted to further analyses if it was initiated at the top left quadrant of the display and terminated in the bottom right quadrant, signaling that the correct referent had been picked-up and then placed at the correct destination. Twelve children were excluded from all trajectory analyses because they either produced more than six errors on the 16 experimental trials or committed errors on each of the four trials in one condition. Although space constraints preclude a complete discussion of error rates for all 43 children, the error types, along with their frequency per condition, are included in Table 1 (with the numbers in parentheses indicating the error frequencies for only the children included in the trajectory analyses). It should be noted, however, that no significant differences existed between the included versus the excluded children in age, vocabulary score, gender, or number of hours using the computer at home or at school (computer familiarity), all *p*'s > .15. As such, we have some evidence to suggest that both language and computer familiarity were not the cause of the processing difficulty.

Table 1: Error types causing a trial to be excluded from all analyses, per condition

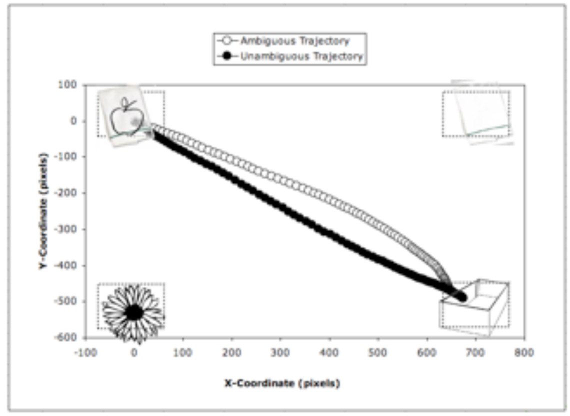
Error Type	1 Referent, Ambiguous	1 Referent, Unambiguous	2 Referent, Ambiguous	2 Referent, Unambiguous
Target Referent Moved to Incorrect Destination	24 (19)	3 (3)	14 (6)	6 (5)
Incorrect Referent Moved to Incorrect Destination	6 (1)	3 (1)	37 (23)	11 (4)
Incorrect Referent Moved to Correct Destination	0 (0)	1 (1)	3 (2)	6 (4)
Picture Representing a Destination was Moved	1 (1)	1 (0)	2 (1)	3 (1)
Erratic Movement Yielding an Uninterruptible Trajectory	13 (5)	10 (3)	15 (10)	11 (5)

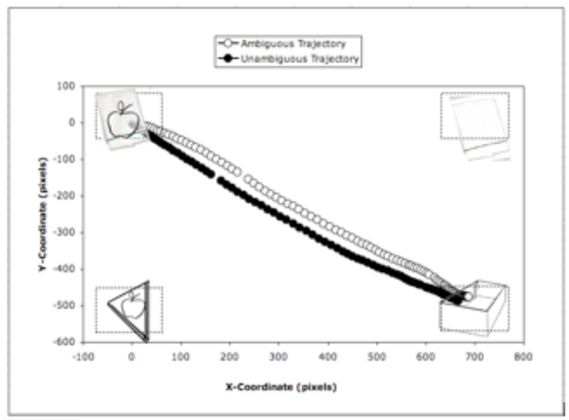
All analyzable trajectories were time-normalized to 101 time-steps by a procedure originally described in Spivey et al. (2005). All trajectories were aligned so that their first observation point corresponded to (0, 0) and their last recorded point to (1,1). Then, across 101 normalized time-steps, the corresponding x and y coordinates were computed using simple linear interpolation.

Context and Garden-Path Effects The mean ambiguous and unambiguous trajectories at each of the 101 time-steps in the top panel of Figure 1 demonstrate that in the one-referent context, like adults, the average ambiguous trajectory was more curved toward the incorrect destination than the average trajectory elicited by the unambiguous sentences. Unlike adults, however, in the two-referent condition (Figure 1, bottom), there still appears to be noticeable attraction toward the incorrect destination for the ambiguous-sentence trajectories. Both of these trends support the notion that participants were garden-pathed by the syntactic ambiguity manipulation regardless of context.

In order to determine whether or not the divergences observed across the ambiguous- and unambiguous-sentence trajectories in the one-referent and two-referent contexts were statistically reliable, we conducted a series of t-tests. Due to the horizontally elongated shape of the overall display, differences in x-coordinates of the mouse movements are somewhat more indicative of velocity differences, and differences in the y-coordinates are more indicative of genuine spatial attraction toward the incorrect referent. As such, analyses were conducted separately on the x- and the y-coordinates at each of the 101 time-steps. In order to avoid the increased probability of a Type-1 error associated with multiple t-tests, and in keeping with Bootstrap simulations of such multiple t-tests on mouse trajectories (Dale, Kehoe, & Spivey, 2007), an observed divergence was not considered significant unless the coordinates between the ambiguous- and unambiguous-sentence trajectories elicited p-values < .05 for at least eight consecutive time-steps.

Figure 1: Examples of one- and two-referent displays with averaged trajectories elicited in each context.





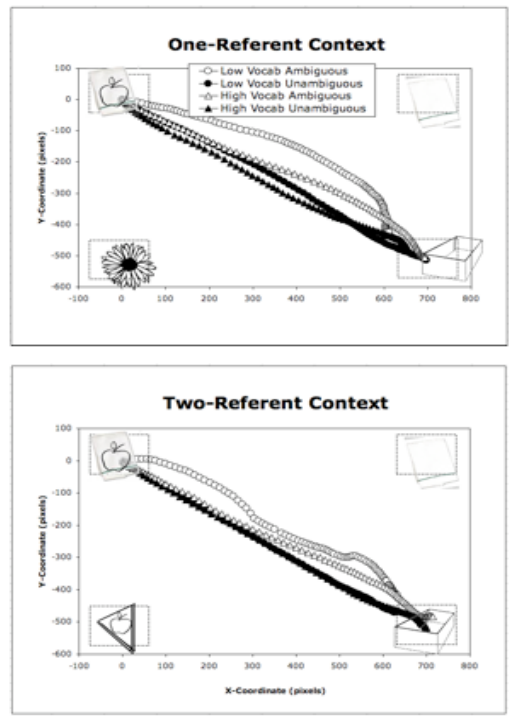
In the one-referent context, no significant divergence ever occurred between the x-coordinates of the ambiguous- and unambiguous-sentence trajectories indicating that, across time, trajectories progressed toward the right side of the screen at approximately the same speed in both sentence conditions. For the y-coordinates, however, the ambiguous- and unambiguous-sentence trajectories diverged significantly from time-steps 43-78, all *t*'s > 2.08, all *p*'s < .05, with y-coordinates being higher (closer to zero, thus closer to the top of the screen) in the ambiguous than in the unambiguous condition. In the two-referent context, significant x-coordinate divergence between the ambiguous- and unambiguous-sentence trajectories occurred from time-steps 9-50, all *t*'s > 2.07, all *p*'s < .05, with ambiguous-sentence trajectories traveling *more quickly* toward the correct destination. However, in the two-referent context, there was no statistically reliable y-coordinate divergence at any of the 101 time-steps. The t-test analyses provide mixed support for the expectation that the data obtained by tracking streaming x,y coordinates would align with the saccadic eye-movements of children in the same paradigm (Trueswell et al., 1999). In the one-referent context, as demonstrated by the significant y-coordinate attraction toward the incorrect destination (commensurate with the large number of looks to the incorrect destination in this condition when examining eye-movements), children do consider, at least temporarily, the destination interpretation of the ambiguous PP. In the two-referent condition, however, there appears to be no statistically significant attraction toward the incorrect destination in the presence of a syntactic ambiguity. This result is puzzling given that on Figure 1 (bottom), there appears to be a divergence between ambiguous- and unambiguous-sentence trajectories and that, when examining eye-movements, children look often to the incorrect destination, even when two referents are present.

One explanation for the incongruence of the results in the two-referent condition with the eye-movement data is that there could exist so much variability in the y-coordinates of the trajectories observed here that not enough power exists to detect divergence, should it be present. In order to reduce the variability surrounding each participant's mean y-coordinate movement in each condition, to avoid concerns associated with multiple comparisons in the t-tests above, and to assess directly the statistical reliability of the crucial Context X Ambiguity interaction, we averaged the y-coordinates recorded from time-steps 34-67 (the middle portion of the movement where, on average, the ambiguous-unambiguous divergences appear most extreme) and used the average y-coordinate response as the dependent measure in a 2 X 2 ANOVA. Average "middle-segment" y-coordinates were closer to the incorrect destination in the one-referent context, suggesting greater uncertainty in the one-referent than in the two referent context, $F(1, 30)=7.58$, $p=.01$. They were also closer to the incorrect destination for the ambiguous over the unambiguous condition, $F(1, 30)=8.26$, $p=.007$. However, the Context X Ambiguity interaction was not significant, $F(1, 30)=1.83$, n.s., suggesting that context was not able to modulate the magnitude of the garden-path effect. Across these two sets of analyses, then, the emerging picture is one whereby the average five-year-old child does not employ referential context to override the VP-attachment bias associated with this manipulation. This observation, along with the large number of errors made in the two-referent ambiguous-sentence condition (Table 1) is in-line with the eye-movement data reported in Trueswell et al. (1999) and Snedeker and Trueswell (2004).

The Influence of Individual Differences in Linguistic Experience on the Use of Referential Context

Using raw vocabulary scores as a proxy for linguistic experience (as is frequently done in the adult processing literature, see MacDonald & Christiansen, 2002, for a discussion), we explored the degree to which those scores could account for difficulty associated with the two-referent context (focusing specifically on the two-referent context here due to space constraints). Noteworthy first is the fact that raw (non-transformed) vocabulary scores significantly predicted the number of error trials in the two-referent ambiguous-sentence condition, $t(38)=-2.77$, $p=.009$, $ß=-.42$, $R^2=.17$[1], but did not predict the number of errors made in the other three conditions. The relationship is negative, such that children with higher vocabularies had fewer error trials than children with lower vocabularies in the two-referent ambiguous condition. This significant relationship implicates vocabulary, and thus language experience, as a strong predictor of who could move the correct referent to the correct destination in the critical two-referent, ambiguous condition.

Figure 2: Averaged elicited trajectories for high and low vocabulary children in one- and two-referent conditions.



In order to investigate the degree to which vocabulary influenced on-line processing, we divided the 31 participants who provided sufficient data for the trajectory analyses into three groups based on their vocabulary scores. We excluded children with vocabulary scores in the middle range in order to make the two groups distinctly different on the vocabulary dimension. No significant difference was found between the high and low vocabulary children in age, gender, or number of hours spent using the computer, either at home or at school, all p's n.s. A 2 (Vocabulary Group) X 2 (Context) X 2 (Ambiguity) ANOVA on the average y-coordinate (spatial attraction index) at the middle segment revealed a marginally significant 3-way interaction, $F(1, 18)=3.10$, $p=.095$. As illustrated in Figure 2, it appears that in the one-referent context, both groups of children garden-path, as evidenced by the divergence between the ambiguous- and unambiguous-sentence trajectories, although the effect is especially marked

[1] This analysis included only the children who were able to complete both tasks.

for the low vocabulary children. In the two-referent context, it appears that more attraction occurs toward the incorrect destination in the low vocabulary children. Although a thorough follow-up to the omnibus ANOVA is perhaps not warranted due to the marginal significance of the interaction term, an interesting statistical trend occurs in the two-referent context. The difference in y-coordinates between the ambiguous- and unambiguous-sentence trajectories was significantly larger for the low vocabulary than for the high vocabulary children from time-steps 34-43, all t's > 2.20, all p's < .05. These results suggest that, at least early in the processing of ambiguous sentences in the two-referent context, high vocabulary children might be more able to use the context cue than low vocabulary children.

General Discussion

As this is the first study to utilize this mouse-tracking paradigm with children, our key observation is that tracking the x, y coordinates of goal directed arm movements does appear to be an informative way to gather fine grained information about the on-line language processing of children. In the one-referent context, converging statistical analyses reveal that the garden-path effect previously observed in young children also manifests itself using this paradigm. In the two-referent context, although no significant divergence between the ambiguous and unambiguous trajectories occurred, context did not reliably interact with ambiguity status in order to modulate the strong VP preference.

This study is also a first step in examining individual differences in the linguistic experiences of young children in relation to their on-line syntactic processing capabilities. Consistent with Snedeker and Trueswell (2004), children with high vocabulary scores, who presumably have more exposure to the linguistic input, appear to be more adult-like in their use of context in the face of a strong lexical bias against NP attachment. The results suggest that children with high vocabulary scores may be better able to use visual context cues, thus reducing the magnitude or frequency of their garden-paths in the two-referent context. Low vocabulary children, however, rely solely on lexical bias, as evidenced by their substantial garden-pathing in both conditions. Taken with the negative correlation between vocabulary and number of errors in the two-referent ambiguous condition, and with hints of vocabulary effects on-line, the results seem to confirm the experience driven proposals of Snedeker and Trueswell. However, more analyses with more children are needed to increase statistical power.

Additionally, these results appear to be commensurate with results from Pearlmutter and Macdonald (1995), which suggested that adults scoring high on verbal span tasks, now thought to be a measure of language exposure as well (see MacDonald & Christiansen, 2002), have better knowledge of more cues than low span adults. The results of the current study suggest that amount of language exposure (perhaps along with other cognitive factors undergoing developmental change, such as memory and attention) plays a role in the development of context use in on-line sentence processing.

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