Individual differences in measures of linguistic experience account for variability in the sentence processing skill of five-year-olds

Sarah E. Anderson,[1] Thomas A. Farmer,[2] Michael Goldstein,[3] Jennifer Schwade[3] & Michael Spivey[4]
[1]Cornell University/[2]University of Rochester/[3]Cornell University/[4]University of California-Merced

The mechanisms underlying developmental transitions in sentence processing are not well understood. Eyetracking research demonstrates that five-year-olds do not use visual scene cues to constrain their interpretation of sentences as adults do (e.g. Snedeker & Trueswell 2004). This research also suggests that developmental differences in cue use may result from differing language experience; thus increased linguistic experience may improve children's use of visual context. Here, we employ computer mouse-tracking to investigate how young children integrate multiple sources of information to extract meaning. Children heard structurally ambiguous sentences while viewing scenes that did or did not support the difficult relative modifier interpretation. As previously reported, children rarely use visual context. Further, children with less language experience made more offline mistakes, implicating language experience as a possible mechanism underlying transitions to adult-like sentence comprehension.

Keywords: Language comprehension; mouse-tracking; language development

1. Introduction

Over the past fifteen to twenty years, a great deal 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 sources of linguistic and non-linguistic information in pursuit of extracting structure and meaning (e.g. Altmann & Steedman 1988; MacDonald, Pearlmutter & Seidenberg 1994; Snedeker & Trueswell 2004; Tanenhaus et al. 1995; Trueswell, Tanenhaus & Garnsey 1994). Until recently, however, a lack of child-appropriate behavioral techniques has hindered the study of young children's on-line processing. Here, we consider whether non-linguistic cues facilitate the comprehension of syntactically ambiguous sentences in children, present data from a new technique to support previous findings on children's sentence processing, and explore individual differences in linguistic experience during the transition to more adult-like sentence processing.

In order to study on-line language comprehension, researchers often present adult subjects with syntactically ambiguous sentences and then examine the sources of information that influence how these sentences are initially interpreted. Take the two following sentences:

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

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

Referential context has been shown to influence where adults initially attach an ambiguous PP. When they hear ambiguous sentences like (1a) in the presence of visual scenes where there is only one referent present (an apple already on a towel), along with an incorrect destination (an empty towel) and a correct destination (a box), adults often look towards the incorrect destination until the second disambiguating PP is heard, at which time their eye-movements get re-directed to the correct destination (Tanenhaus et al. 1995; Trueswell et al. 1999). Looks to the incorrect destination indicate "garden-pathing," or, initially incorrect attachment of the PP to the verb phrase. Looks to the incorrect destination do not occur when the instruction is unambiguous, as in (1b).

Looking patterns are markedly different when the visual context contains two possible referents (e.g. 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 one. As predicted by various instantiations of referential theory (Altmann & Steedman 1988; Spivey & Tanenhaus 1998), two possible referents require that the similar entities are discriminated, thereby forcing a modifier interpretation on the initial PP (NP-attachment).

While adults use visual context to resolve temporary ambiguities with less common but correct interpretations of sentences, children do not immediately use visual context to disambiguate temporarily ambiguous sentences in the same way as adults. Regardless of the number of referents in the visual scene, children still garden-path when hearing an ambiguous sentence (Trueswell et al. 1999).

However, they behave like adults in regard to another cue. Lexical biases, or the frequency with which a verb (e.g. *put*) takes a prepositional object (*on the towel*) in naturally occurring language, influence the degree to which adults and children experience a garden-path effect. When the lexical bias of a verb strongly supports VP-attachment, both adults and children prefer the VP-attached interpretation of the PP (Britt 1994; Snedeker & Trueswell 2004). For example, when hearing a globally ambiguous sentence with a VP-attachment biased verb like *tickle*, e.g. *Tickle the pig with the fan*, both adult and child participants will pick up a fan from the visual display and use it to tickle a pig (VP-attachment) more often than they will tickle a second pig that is holding a fan in the visual display (NP-attachment), thus demonstrating a preference for resolving the ambiguity with VP-attachment. If the verb does not typically take a prepositional object, for instance *choose*, which favors NP-attachment (Snedeker & Trueswell 2004), children and adults prefer the NP-attached interpretation of the PP. Therefore, in *Choose the cow with the stick*, participants attach the PP to the NP and pick up the cow holding the stick from the visual display (rather than using another stick present in the visual display to pick up a second cow). Unlike adults, however, the scene-based referential context does not interact with lexical bias in the verb in determining children's initial interpretations. Although children show remarkable sensitivity to verb biases, context does not further facilitate children's initial attachment preference (Snedeker & Trueswell 2004).

However, in some experimental settings, children do seem to use referential context in an adult-like way. For instance, when children do not see a visual scene with two referents until after hearing the entire ambiguous sentence, they perform more like adults in the two-referent ambiguous-sentence condition (Meroni & Crain 2010). Hearing an ambiguous sentence first may simplify the task by allowing children to deal with the inputs one at a time and so ultimately incorporate the visual scene information into comprehension of the sentence. These results imply that processing efficiency is linked not only to language comprehension (Fernald, Perfors & Marchman 2006; Hurtado, Marchman & Fernald 2008; Marchman & Fernald 2008), but also to the ability to use multiple cues during language comprehension.

Children are not adult-like in their sentence processing ability, but it is unclear what mechanisms underlie the transition from child- to adult-like sentence processing. Snedeker and Trueswell (2004) suggested that the most reliable sources of information for children, specifically the lexical bias of ambiguity producing verbs, are relied on more heavily than less reliable information, e.g. the referential context. Such an explanation implies a role for linguistic experience: children with more linguistic experience are likely to have come across either more diverse examples of syntactic constructions or more examples of visual context as reliable disambiguating cues. As a result, children with more linguistic experience should behave in a more adult-like way in the two-referent, ambiguous condition (Snedeker & Trueswell 2004; Trueswell et al. 1999).

Previous research supports this prediction, demonstrating that individual differences in linguistic input predict children's mastery of more complex sentences (Huttenlocher et al. 2002). Specifically, individual differences in children's comprehension of multi-clause sentences is related to the proportion of such multi-clause sentences in parental speech. Children whose parents use such sentences more often have better mastery of them. Exposure to more complex syntactic input results in increased mastery. The present study aimed to establish a more explicit link between individual differences in linguistic experience and more adult-like use of visual cue information in the processing of complex sentences. If exposure in the input is what drives the comprehension system toward adult-like behavior, children with more linguistic experience should make a more adult-like use of context than children with less linguistic experience.

In the adult literature, researchers use vocabulary scores to index linguistic experience (MacDonald & Christiansen 2002). In children, vocabulary growth is related to the extent and diversity of linguistic experience, at least until the age of two (Hoff 2003; Fernald & Marchman, this volume). This suggests that vocabulary scores are a reasonable approximation of linguistic experience, in that children with richer linguistic experience have higher vocabulary scores. More recent research demonstrates a link not only between early maternal input and later vocabulary size (Hurtado et al. 2008), but also between vocabulary size and language processing efficiency (Fernald et al. 2006; Hurtado et al. 2008; Marchman & Fernald 2008). Eighteen-month-old children of parents who spoke to them more often and produced more complex constructions had larger vocabularies at 25 months (Hurtado et al. 2008; Fernald et al. 2006) and at eight years of age (Marchman & Fernald 2008). Also, children who heard more input early on had greater processing speed in language comprehension tasks as they got older (Hurtado et al. 2008). Although many factors may drive development over time, previous research suggests that linguistic experience is a legitimate starting place for looking at individual differences in sentence processing within a single age group.

2. A new methodology for use with children

Although eye-tracking has provided invaluable child-performance data, the technique can be expensive, involves slow hand-coding of data, and sometimes elicits parental objections. As a supplement to eye-tracking, monitoring the continuous nonlinear trajectories recorded from the streaming *x, y* coordinates of computer-mouse movements can serve as an indicator of underlying cognitive processes in spoken word recognition (Spivey, Grosjean & Knoblich 2005), categorization (Dale, Kehoe & Spivey 2007), adult syntactic processing (Farmer, Anderson & Spivey 2007), and various higher-level social phenomena (Freeman et al. 2008; Wojnowicz et al. 2009). Unlike saccadic eye-movements, mouse movements are generally smooth, continuous, and can curve substantially mid-flight. This dense sampling methodology allows graded spatial attractions to emerge within single trials. For example, 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. By recording the *x,y* coordinates of the mouse as it moved with the goal-directed hand motion to click on the appropriate object, smooth competition between the partially active underlying representations are revealed in the shape and curvature of the hand-movement trajectories. These properties of tracked mouse-movements provide crucial benefits in that they allow a fine-grained, graded response pattern to emerge within an individual trial.

Although children can use a computer mouse at 3;6 years, on average, and the onset of autonomous computer use is approximately 3;8 years (Calvert et al. 2005), the degree to which this cheap, portable, and accessible mouse-tracking methodology can be used to study complex cognitive phenomena in young children remains to be seen. Here, we exploit mouse-movement trajectories in the visual-world paradigm (Tanenhaus et al. 1995) to determine their efficacy with children in detecting differences in processing, in complex cognitive tasks.

3. The current experiment

We employed the mouse-tracking methodology to monitor the motor output of children as they moved objects around a natural scene in response to ambiguous (1a) and unambiguous (1b) spoken instructions. To hold lexical bias constant, instructions contained only the verb *put*, strongly biased toward VP-attachment (for example, attaching the first PP *on the towel* to the verb *put*, resulting in a garden-path effect). The computer mouse-movements made towards either the target or distracter objects in the visual scene provide an index of what children are attending to, moment to moment, as they interpret the utterance. Trajectories that veer towards the incorrect goal location while the correct object is picked up and moved, ultimately, to the correct location in the display, indicate a garden-path effect, signaling some consideration of VP-attachment.

This is the first study to use the mouse-tracking method with young children, and we predicted the results would be similar to those of eye-tracking studies. In the one-referent context, we expected significant curvature toward the ultimately incorrect destination for ambiguous sentences (1a), relative to the unambiguous control condition (1b), signaling some consideration of VP-attachment. In the two-referent context, we predicted that if mouse-movement data provide results similar to the eye-movement data elicited from children in previous studies (Trueswell et al. 1999), then we should detect significant ambiguous-sentence trajectory curvature toward the incorrect destination, relative to the unambiguous control condition.

In addition to verifying that mouse-tracking is a suitable methodology for examining children's comprehension of complex sentences, we also examined the role of linguistic experience on children's performance in this task. While previous research suggests that linguistic experience plays a crucial role in the transition from child- to adult-like sentence-comprehension (Snedeker & Trueswell 2004), this is the first experiment to explicitly test such predictions within a single age group using an individual differences approach in relation to performance on a visual-world task. To examine the role of linguistic experience on children's performance, children also completed a receptive vocabulary test. As described above, we use vocabulary scores as a proxy for linguistic experience, predicting that children with higher vocabulary scores would have more adult-like use of context in the two-referent, ambiguous-sentence condition.

4. Method

Participants. Forty-three participants, 19 females and 24 males, between the ages of 4;8 and 5;10 months old (M = 5;3) took part in this experiment. We recruited children from the developmental lab's birth announcement database and local school systems. They came from mostly middle to upper middle SES families. Each child received a small toy for participating. One additional child was excluded from the analysis due to refusal to participate in the mouse-tracking task. Twelve other children were excluded from the trajectory analysis because they produced too many incorrect mouse trajectories.

Materials and procedure. We adapted and digitally recorded 16 experimental items from Spivey et al. (2002). We made each item 'child-friendly' by substituting, for potentially unfamiliar referents, referents included in the MacArthur-Bates Communicative Development Inventory, a widely used parental-report of productive vocabulary for children aged up to 2;6 (Fenson et al. 1994). We recorded ambiguous (1a) and unambiguous instructions (1b) that corresponded to each of sixteen experimental scenes (see Spivey et al. 2002 for details). We varied the visual scenes corresponding to the 16 experimental items to produce a one-referent condition and a two-referent condition for each one. 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 we replaced the distracter by a second possible referent (e.g. an apple on a napkin). We also created 16 distracter scenes designed to accompany filler sentences. These scenes used different combinations of objects from the experimental trials and from a set of new, easily recognized objects.

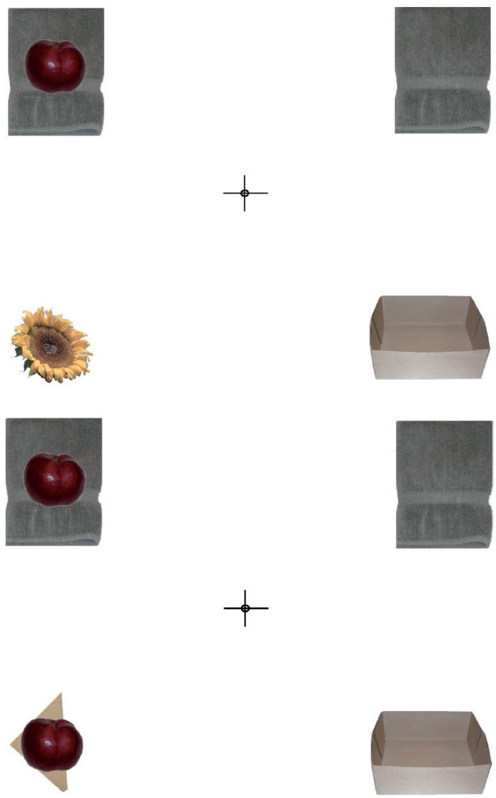

Figure 1. Example of one- (top) and two- (bottom) referent displays shown to children

A female adult, using age-appropriate child-directed speech, recorded the spoken instructions using the speech synthesizer program Audacity. Children sat at a child-sized table in front of a computer monitor. Macromedia Director MX presented the visual context and sound files on an Apple G4 computer. We used a small, portable mouse to collect mouse movements. A visual display containing all items associated with each instruction, presented auditorily, appeared on the monitor (Figure 1). 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, an experimenter repositioned the mouse itself at the center of a small sticker on the table. This repositioning ensured that the mouse cursor always started in the same place for each trial and minimized the possibility that the participants would run out of room to move the mouse on the table during 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).

We also created 16 additional filler scenes, and participants heard three scene-appropriate unambiguous filler instructions accompanying 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 provided a natural break in the experiment and helped keep the child motivated.

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 prevented participants from detecting the regularity created by the object placements in experimental trials. In addition to the movement used in the experimental instructions, eleven distinct movements were possible in the visual scene across trials (i.e. bottom right-hand corner to top right-hand corner), and an approximately equal number of filler sentences were assigned to each of these. For each child, 10 sentences required an object in the upper left-hand corner to be moved to the upper right corner of the display, 8 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. We used pictures of real objects, taken by a digital camera and edited in Adobe Photoshop, to construct the images in the visual scenes. Visual stimuli subtended an average of 5.96 x 4.35 degrees of visual angle, and were 14.38 degrees of visual angle diagonally from the central cross. Mouse movements were recorded at an average sampling rate of 40 Hz.

We counterbalanced the experimental items across four presentation lists. Each list contained four instances of each possible condition, but only one version of each sentence frame and the corresponding visual context. Participants were randomly assigned to one of the four presentation lists, and the presentation order of the items within each list was randomized for each participant. Each participant saw three practice items at the beginning of the experiment.

Each child also completed the Peabody Picture Vocabulary Test, PPVT-III (Dunn & Dunn 1997), a widely-used and reliable test of receptive vocabulary. Participants heard a spoken word and pointed to the correct referent from a display of 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. Parents completed a form providing information about the child's computer use and their demographic information. The entire session lasted approximately 30 minutes.

5. Results

Data screening and coding. Mouse movements were recorded during the grab-click, transferral, and drop-click of the referent object in 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 (location of the correct referent) and terminated in the bottom right quadrant (location of the correct destination), signaling that the correct referent had been picked up and 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. The error types of all 43 children, along with their frequency per condition, are given in Table 1 (numbers outside of the parentheses indicate the errors of children included in the trajectory analyses, and the numbers in parenthesis indicate the error frequencies for all the children). There were no significant differences 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 ps $> .15$. Thus, age, vocabulary, and computer familiarity were unlikely causes for refusal to participate or for exclusion from the on-line analysis.

Table 1. Error types causing a trial to be excluded from all analyses, per condition. The number in parentheses is the number of error trials from children excluded from the final on-line analysis; the number outside the parentheses is the number of error trials the thirty-one children contributing to the online analyses

Error type	**1 Referent, ambiguous**	**1 Referent, unambiguous**	**2 Referent, ambiguous**	**2 Referent, unambiguous**
Target referent moved to incorrect destination	19 (24)	3 (3)	6 (14)	5 (6)
Incorrect referent moved to incorrect destination	1 (6)	1 (3)	23 (37)	4 (11)
Incorrect referent moved to correct destination	0 (0)	1 (1)	2 (3)	4 (6)
Picture representing a destination was moved	1 (1)	0 (1)	1 (2)	1 (3)
Erratic movement yielding an uninterruptible trajectory	5 (13)	3 (10)	10 (15)	5 (11)

Children made significantly more errors, $F(1,42) = 11.96$, $p < .01$, in the two-referent ($M = 1.26$, $SD = 1.19$) than in the one-referent condition ($M = .72$, $SD = 1.26$). They also made significantly more errors, $F(1,42) = 20.65$, $p < .01$, in the ambiguous-sentence condition ($M = 1.34$, $SD = 1.13$) than in the unambiguous one ($M = .64$, $SD = .95$). However, this interaction was not significant, $p > .37$. A similar trend emerged for the 31 children included in the on-line analyses. They made significantly more errors, $F(1,30) = 9.105$, $p < .01$, in the two-referent conditions ($M = .98$, $SD = 1.03$) than in the one-referent conditions ($M = .55$, $SD = .76$). They also made significantly more errors, $F(1,30) = 17.17$, $p < .01$, in the ambiguous-sentence conditions ($M = 1.01$, $SD = .99$) than in the unambiguous ones ($M = .44$, $SD = .74$). However, the interaction was again not significant, $p > .48$. These error rates are similar to those found in research with eye-tracking (Snedeker & Trueswell 2004; Trueswell et al. 1999). Ambiguous sentences elicit more off-line errors than unambiguous ones because of the increased linguistic complexity of the ambiguous sentences. Similarly, the two-referent conditions elicit more off-line errors than the one-referent ones, because, in part, the presence of two possible referents in the visual scene increases the complexity of the referential context.

All analyzable trajectories were time-normalized to 101 time-steps using the procedure in Spivey et al. (2005). All trajectories were spatially aligned so that the first observation point corresponded to the *x,y* coordinates of (0, 0). We then computed the corresponding x and y coordinates across 101 normalized time-steps, using linear interpolation.

Context and garden-path effects. The mean ambiguous- and unambiguous-sentence trajectories at each of the 101 time-steps in the top panel of Figure 2 demonstrate that in the one-referent context, like adults, the average ambiguous-sentence trajectory was more curved toward the incorrect destination than the average trajectory elicited by unambiguous sentences. Unlike adults, however, in the two-referent condition (Figure 2, bottom), there still appears to be noticeable attraction toward the incorrect destination for ambiguous-sentence trajectories. Both these trends support the notion that the children were garden-pathed by the syntactic ambiguity manipulation, regardless of context.

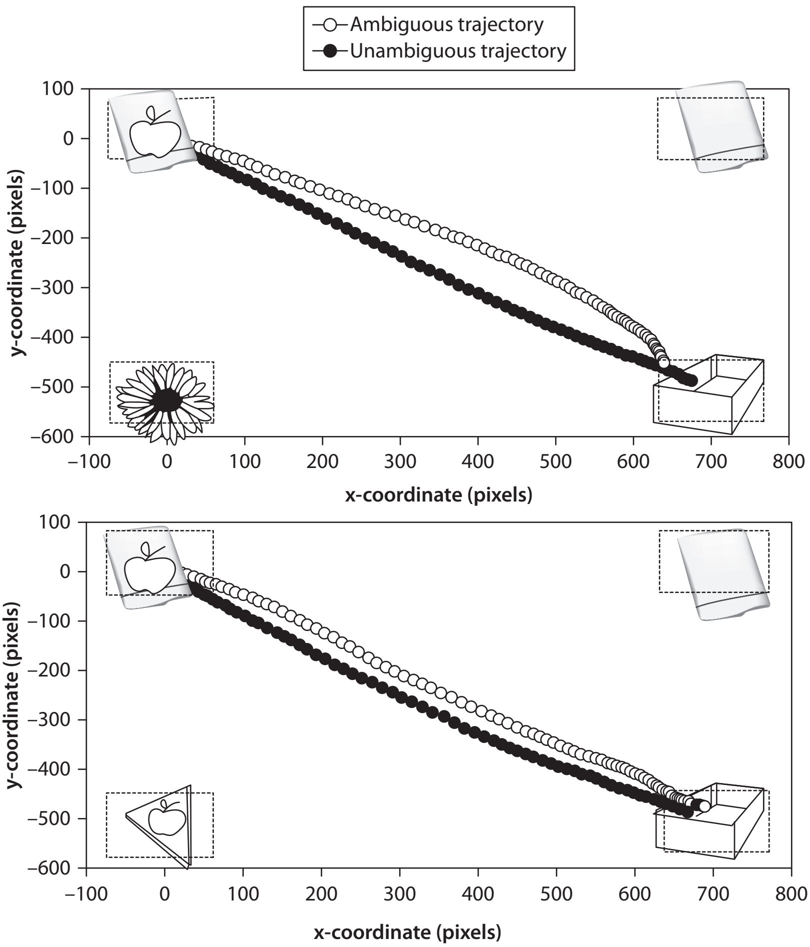

Figure 2. Time-normalized ambiguous- and unambiguous-sentence trajectories elicited in the one-referent (top) and two-referent (bottom) contexts

In order to determine whether the divergences observed across the ambiguous- and unambiguous-sentence trajectories in the one- 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 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 *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 et al. 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.

In the one-referent context, no significant divergence occurred between the *x*-coordinates of the ambiguous- and unambiguous-sentence trajectories. This indicated 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 higher *y*-coordinates (closer to zero, thus closer to the top of the screen) in the ambiguous than in the unambiguous sentence condition (Figure 2). In the one-referent context, the divergence of the average *y*-coordinates of the ambiguous-sentence trajectory away from the unambiguous-sentence trajectory and towards the incorrect destination is indicative of the garden-path effect also observed in eye-tracking research (Snedeker & Trueswell 2004; Trueswell et al. 1999).

In the two-referent context, significant *x*-coordinate divergences 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. This suggests that the two-referent context did not induce the expected garden-path effect. This was surprising given the data from previous eye-tracking studies which showed that children often looked to the incorrect destination, temporarily considering it as the goal location of the action, even when two referents were present.

Thus, the *t*-test analyses provide mixed support for the expectation that the data obtained from streaming *x,y* coordinates in mouse-tracking would align with children's saccadic eye-movements in the visual world paradigm (Trueswell et al. 1999). In the one-referent context, children do consider, at least temporarily, the destination interpretation of the ambiguous PP. In mouse-tracking the curvature towards the incorrect destination is commensurate with the large number of looks to the incorrect destination in this condition when examining eye-movements. 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 surprising given previous research and given that, in Figure 2 (bottom), there appears to be a divergence between ambiguous- and unambiguous-sentence trajectories.

One explanation for the incongruence of our results with previous eye-tracking results in the two-referent condition is that the amount of variability in the *y*-coordinates of our trajectory data exceeds the power 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 (Context) x 2 (Ambiguity) repeated-measures 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, $F(1, 30) = 7.58$, $p = .01$. The *y*-coordinates 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 does not modulate the magnitude of the garden-path effect. These data support earlier eye-tracking data and suggest that children still experience the garden-path effect in the two-referent ambiguous context.

Taken together, these results reveal spatial attraction toward the ultimately incorrect destination in response to ambiguous sentences when compared to the unambiguous condition, regardless of context. This suggests that, like adults, children experience a garden-path effect in the one-referent, ambiguous-sentence condition, but that, unlike adults, they do not readily use context to disambiguate the sentence in the two-referent ambiguous-sentence condition.

Individual differences in linguistic experience and use of referential context. As the trajectory data demonstrate, unlike adults, children do not readily incorporate visual context into their comprehension of an ambiguous sentence. Earlier research by Snedeker and Trueswell (2004) suggested that linguistic experience might play a role in the transition to more adult-like behavior. Their proposal was that children with more linguistic experience would be able to use either more diverse syntactic constructions or more instances of visual context that then provided reliable disambiguation. Children with more linguistic experience should behave in a more adult-like way, especially in the two-referent, ambiguous-sentence condition that is typically the most difficult for young children. Here, we established a more explicit empirical link between individual differences in linguistic experience and adult-like processing performance, by using vocabulary scores as a proxy for linguistic experience: higher scores indicated greater linguistic experience (e.g. Hoff 2003).

With the vocabulary scores, we explored the degree to which these could account for difficulty associated with the most difficult condition for this age, the two-referent context (Snedeker & Truesswell 2004; Trueswell et al. 1999). First, we examined the error rates and raw (non-transformed) vocabulary scores for all the participants. The raw vocabulary scores significantly predicted the number of error trials only in the two-referent ambiguous-sentence condition, $t(38) = -2.77$, $p = .009$, $\beta = -.42$, $R^2 = .17$ (see Figure 3). The relation is a negative one, such that children with larger vocabularies have fewer errors in the two-referent ambiguous condition than children with smaller vocabularies. This implies that vocabulary size, and thus linguistic experience, is a predictor of which children would move the correct referent to the correct destination in the critical two-referent, ambiguous-sentence condition.

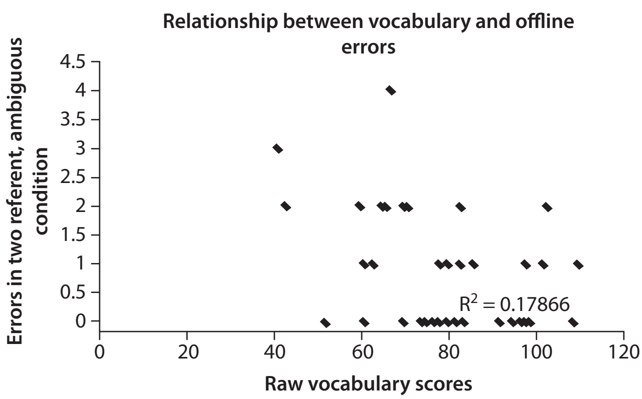

Figure 3. Relations between vocabulary and number of errors in the two-referent, ambiguous-sentence condition. Children with higher vocabulary scores (richer linguistic experience) made fewer errors only in this condition

We also examined the relation between raw vocabulary scores and an online measure of trajectory divergence. For the children who contributed to the on-line analyses, raw vocabulary scores did not predict the degree of trajectory curvature toward the incorrect destination (indexed by calculating the average maximum deviation value for ambiguous-sentence trials, per subject) in either the one- or two-referent ambiguous-sentence conditions.

6. Discussion

The data contribute to an emerging picture where the average five-year-old child does not employ referential context to override the VP-attachment bias. Along with the large number of errors made in the two-referent ambiguous-sentence condition (Table 1), this is consistent with the eye-movement data reported in Trueswell et al. (1999) and Snedeker and Trueswell (2004). The fact that the trajectory data are commensurate with previously reported eye-tracking data lends support to the notion that the mouse-tracking method is feasible and reliable for getting at underlying cognitive processes in young children. However, we do not advocate, or foresee, the replacement of eye-tracking methods by mouse-tracking. Rather, the two techniques could be used in a complementary (even simultaneous) fashion in order to more fully explore the nature of the complex interactions associated with high-level cognitive processes.

Our results provide further insight into the nature of the developmental mechanisms responsible for the transition from child-like to more adult-like sentence processing skill. Linguistic experience significantly predicts off-line errors in the two-referent, ambiguous-sentence condition that children found most difficult. Children with more linguistic experience produced fewer errors here than children with less linguistic experience. This was not of the case for any other conditions. To the degree that individual variations in receptive vocabulary serve as a proxy for variability in linguistic experience, these data suggest that richer linguistic experiences render children more adult-like in their use of referential context.

More broadly, our data dovetail with research into the relation between early input and later language processing efficiency (Hurtado et al. 2008). In a longitudinal study, Hurtado and her colleagues (2008) found a link between maternal speech and children's vocabulary size. Spanish learning 18-month-olds whose mothers spoke relatively more to them had larger vocabularies at 24 months than children whose mothers spoke relatively less to them. Also, children with larger vocabularies at 24 months were faster to identify familiar words in speech. These data support our proposal that children with richer linguistic experience have correspondingly larger vocabularies, and that these early experiences influence later language comprehension. Both quality and quantity of the mother's speech to the child at 18 months predicted children's language processing at 24 months (Hurtado et al. 2008). Children who received relatively more maternal input at the first time point were faster in online comprehension tasks at the second time point. Our research complements this work, extending the link between early input and later processing efficiency to five-year-old children. In our research, larger vocabularies predicted lower off-line error rates in the difficult two-referent, ambiguous-sentence condition.

While these findings take an important step toward understanding the mechanisms underlying the transition from child to adult-like sentence processing abilities, several questions remain. How does linguistic experience facilitate this change? Linguistic experience could increase children's reliance on visual scene information, or decrease their reliance on lexical bias, or both. As children are exposed to a greater variety of sentence constructions in an increasing number of communicative contexts, their sensitivity to and reliance on cues other than verb-based lexical biases, such as visual context, could increase. First, the statistical relations between language and properties of co-occurring visual scenes are likely to be substantially sparser, and thus more difficult to learn, than the statistical information associated with verb-biases in child-directed speech. As a result, efficient utilization of scene-based referential information in language comprehension may simply require more experience with contextualized linguistic processing before visual-scene based information can act as a viable cue in interpretation. A second possibility is that linguistic experience decreases reliance on lexical bias information. As children are exposed to richer linguistic experiences, their reliance on lexical bias in verbs should decrease as they encounter more instances where lexical bias is not the only reliable cue. Third, linguistic experience may do both. As linguistic experience increases, reliance on other cues, like visual scene information, is increased *and* reliance on lexical bias cues decreased. Children with more linguistic experience with syntactic constructions, specifically with the verb *put* followed by a PP both as VP-attachment and as NP-attachment, may also have had more experience with the relation between visual context and co-occurring language. This possibility suggests that a child with greater linguistic experience is more likely to have experienced (a) more diverse examples of syntactic constructions (decreasing reliance on verb bias) and (b) more examples of visual context as a reliable disambiguating cue (increasing reliance on visual context cues).

The current results do not distinguish among these possibilities, but computational modeling may allow for more explicit examination of changing weights according to each of these options. By adapting the model used in earlier adult sentence processing research (Farmer, Anderson & Spivey 2007), we could examine individual weights within the model and compare them to the present findings. This research is currently underway.

What other sources of individual-based variability could contribute to the transition to adult-like processing? Are children able to inhibit an appealing, or more frequent, but ultimately incorrect response, in order to select the correct referent and move it to the correct destination without experiencing the garden-path effect? Individual differences in cognitive control reliably predict adult performance on ambiguous sentences (Novick et al. 2005). For example, adults who score higher on cognitive control tasks exhibit less difficulty in recovering from misinterpretation of an ambiguity.

Similarly, recent cross-linguistic research suggests that cognitive control may be more important than lexical bias information in accounting for differences between children's and adult's sentence processing skills (Choi & Trueswell 2010). When experimenters used eye-tracking to compare the performance of Korean-speaking adults and children, they found that Korean five-year olds do not use late-arriving verb bias information to override early-arriving syntactic information, producing results similar to those of earlier eye-tracking research with English-speaking five-year-olds. These results are striking because English-speaking children produce similar looking data, but for different reasons; they do not use late arriving syntactic information to override early arriving verb bias information. Even when the lexical bias information is presented late, children persist in garden-pathing in the two-referent, ambiguous-sentence condition. This suggests that other sources of individual differences, namely cognitive control, could be more important than verb bias in accounting for their use of referential context with more adult-like performance.

Cognitive control may also influence how quickly children can move their attention around a visual scene. Previous research suggests that the ability to shift visual attention may play an important role in using referential context effectively. For instance, when children are prevented from viewing the scene until they have heard the entire sentence, they perform in a more adult like fashion in the two-referent, ambiguous-sentence condition (Meroni & Crain 2010). Inhibiting visual attention to a salient object, thus increased cognitive control, may be crucial in dealing with the complexity of the two-referent ambiguous-sentence condition.

While there is still much research to be done, the current results provide further evidence, converging with eye-tracking data, that five-year-olds do not use visual cues to disambiguate an ambiguous sentence. These data also suggest that individual differences in linguistic experience play a role here: Since vocabulary scores predict the degree to which children are able to move the appropriate item to the appropriate destination in the two-referent, ambiguous-sentence condition, linguistic experience likely contributes to the transition from child-like to more adult-like processing.

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