Incremental Referentially-Based Processing in Children: Evidence from Eye Monitoring

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1. Introduction

On the face of it, the fields of sentence processing and language acquisition should have a great deal to say to each other, as both must confront the interaction of the grammatical linguistic system with nonlinguistic mechanisms and limitations. It is to be expected that the learning of language and its processing would be interrelated. From one direction, the process and developmental sequence of language acquisition could plausibly affect the ease of processing of specific linguistic structures and representations. From the other direction, it would seem impossible to truly characterize the nature of linguistic input that is available to the child without an understanding of how the incoming signal is structured and processed by the child. However, the reality is that while issues of processing and acquisition have sometimes been intertwined in investigations of speech processing at the level of phonological units in the area of infant speech perception (Morgan & Demuth, 1996), there has been relatively little crossover between the fields in the areas of syntax and semantics, nor influence from progress in one area to the other.

While a complete explanation for this dynamic is undoubtedly difficult to achieve, it seems that several factors can be identified as contributing to this separation. The historical development of the goals and empirical bases of these fields has given rise to two very different sets of driving questions and methodological paradigms. For instance, from its beginnings in the 1960s, sentence processing has been concerned largely with accounting for the processing difficulty of perfectly grammatical sentences such as *"The boy the girl the dog bit saw chased"* or *"The horse raced past the barn fell"*. These investigations have tended to focus on limitations that arise as a result of the temporal pressures on processing language on-line. As a result, the phenomena of interest were focused on processing-specific mechanisms, with a downplaying of the role of linguistic representation. The field of language acquisition, on the other hand, has traditionally been viewed as explaining the transition from an immature representational system to a fully mature one, with emphasis on the characterization of a system of grammar at various stages in the acquisition process. Processing explanations have been frequently invoked to account for child data (e.g. Bloom, 1993), but this has typically been done

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outside of the context of what is more generally known about processing mechanisms in adults, and more to the point, any investigation of general processing constraints and mechanisms for children.

These differences in emphases have led to and exacerbated the separation of these two fields, particularly in that they have led to the development of experimental paradigms with very little overlap. In sentence processing, due to the preoccupation of the field with temporal dynamics, processing studies have relied on temporally sensitive measures detecting processing load differences or evidence of temporary misanalysis. Thus, the toolkit of the typical sentence processing researcher includes experimental methodologies such as reading time studies, or tasks involving secondary tasks, such as phoneme monitoring (where subjects are required to simultaneously comprehend and monitor a sentence for the presence of a particular phoneme), or crossmodal tasks, where subjects simultaneously listen to a sentence and make a response pertaining to some unrelated word that is presented visually on a screen at some point during the sentence. These tasks are understandably difficult to administer to young children (though see McKee, Nicol, & McDaniel (1993) and Swinney & Prather (1989) for successful applications of crossmodal priming techniques to child populations, and Tyler & Marslen-Wilson (1981) for some interesting results with speech monitoring tasks). In contrast, language acquisition paradigms have focused on the outcome of producing or interpreting a sentence as a way of revealing the representations that are assigned to it. Relevant methods have included looking at patterns of production data, or examining children's interpretations of sentences as exhibited by act-out tasks or picture identification tasks. The lack of overlap between these research paradigms and the dearth of comparable sources of data across the two disciplines have made more coordinated progress impossible.

Unfortunate though this lack of overlap has been, there is good reason to expect significant shifts in the relationship between these fields. For instance, explanations for core language processing phenomena are increasingly incorporating components that reflect the effect of experience with language, and away from parsing-specific accounts (e.g. for an overview of parsing preferences and frequency biases of various linguistic structures, see MacDonald, Pearlmutter, & Seidenberg, 1994). In addition, there has been growing interest in the on-line processes involved in semantic and referential interpretation, rather than structural assignment alone. This has forced the field to develop experimental paradigms that are at once temporally sensitive, but also reflect interpretive reflexes of processing language.

It was this shift in interest towards on-line interpretation that resulted in the development of a procedure that measures very directly the process of mapping linguistic expressions to their corresponding referents in the world (see Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). It involves monitoring subjects' eye movements to a visual scene as they respond to spoken instructions by manipulating objects on a vertical board or table top. The technique is useful because subjects typically look at the objects that serve as referents for the linguistic expressions they hear, so the eye movement data can provide a measure of how long it takes to establish reference under various conditions, as well as what other objects are being considered as possible referents. In addition, it allows for the systematic manipulation of aspects of the linguistic stimuli, as well as aspects of the visual model, that is, the set of possible referents. This makes it possible to directly investigate the interaction between circumscribed discourse models and language structure in the course of on-line language processing.

This eye-monitoring methodology combines task simplicity with extraordinary sensitivity to the time-course of processing, making it an ideal tool for studying language processing in young children. In addition, the task has proven to be highly versatile with adults. Studies reveal sensitivities to low-level lexical information (Allopenna, Magnuson, & Tanenhaus, 1998), to information pertaining to the disambiguation of syntactic and semantic indeterminacies (Eberhard, Spivey-Knowlton, Sedivy, & Tanenhaus, 1995; Tanenhaus et al., 1995), as well as to high-level information associated with discourse context (Sedivy et al., 1999). Thus, extending this experimental paradigm to research with young children is likely to have a widespread impact on the study of language processing and language acquisition in children.

The body of work cited above demonstrates a central aspect of human language processing: that it is a processing system where linguistic expressions are continuously being mapped to referents in a model (in this case a visually-accessible one), with information from the model rapidly being used to resolve temporary referential indeterminacies. This model-based view of processing runs counter to more traditional views of on-line processing, which hypothesized serially-ordered encapsulated sub-processors which would initially abstract from the input a representation of its syntactic structure independently of semantic or interpretive constraints (e.g. Forster, 1979; Frazier, 1987).

It is at present an open question as to whether the processing systems of young children exhibit architectural organizations that mirror the adult system. Tyler & Marslen-Wilson (1981) argue, based on word-monitoring techniques in spoken language, that children process language within an interactive, interpretation-driven system that integrates syntactic, semantic and pragmatic information as soon as such information becomes available. This conclusion runs counter to hypotheses that the apparent lack of control over certain pragmatically-sensitive syntactic structures is due in part to either the lack of such knowledge in the young child, or the fact that it is accessible only late in the processing system (Goodluck, 1990.)

Work in the headmounted eyetracking paradigm is just beginning to be carried out with child populations, with intriguing results. Trueswell, Sekerina, & Hill (1999) show data suggesting that children's processing is generally referentially-driven. They monitored children's eye movements to objects in a display in response to spoken syntactically-ambiguous stimuli such as "Put the frog on the napkin into the box", and found that children's eye movements were generally related to the information available in the speech stream as the instruction unfolded in time. However, they also found that children did not make use of referentially-based information in the visual scene that typically provides disambiguating information for adults. One possible explanation for these results is that substantive architectural differences are found in the processing mechanisms in children and adults. Alternatively, the results may lie in differences in the degree of knowledge of pragmatic referential constraints, or in different biases involved in the representations of linguistic structures or verb argument preferences.

In the current study, we directly test the hypothesis that like adults, children exhibit the property of incremental referential processing, that is, the mapping of a linguistic expression to its semantic denotation proceeds on the basis of very partial input, with hypotheses being generated immediately.

2. Method, Materials and Procedure

The logic underlying the current study was similar to experimental paradigms designed to look at evidence of incremental syntactic processing. We created a situation which involved a potential temporary referential indeterminacy, and then looked for evidence that children would attempt to resolve the indeterminacy immediately. Consider, for instance, a sentence such as Bever's (1970) notorious example "*The horse raced past the barn* fell." The standard explanation for difficulty with this sentence is that people initially misanalyze the italicized portion of the sentence, and are forced to revise later, often without the ability to recover from this misanalysis. We can ask the same question for referential indeterminacies – namely, is there evidence of initial misanalysis, or interference from possible referents that do not end up corresponding to the target of a referential phrase?

The experimental design was very similar to one used by Eberhard et al. (1995) to investigate incremental referential processing in adults. It involved manipulating the visual display such that the point at which it becomes possible to unambiguously identify the target referent is varied. To illustrate, consider the example of a visual display found in Figure 1, with the accompanying instruction "Pick up the red turtle." It is in principle possible to identify the target object upon processing the word "red", as there is a single red object in the display. However, a referential indeterminacy can be introduced at precisely this point in the speech stream if the accompanying display contains a second red object (Figure 2).

Figure 2 shows an example of a different display, in which the disambiguation point is the head noun "turtle" rather than the color adjective. If referential interpretation is indeed taking place incrementally, this creates the potential for indeterminacy at a particular point in the utterance, namely, at the word "red", as there is more than one potential referent for this expression. Thus, if subjects are computing the denotation of "red" at this point, we expect to see evidence of consideration of both possible referents. We can then compare this display with a version in which a similar indeterminacy does not arise, namely, one in which there is only one red object, as in Figure 1. In contrast, if referential interpretation is delayed until the end of the noun phrase, or the head noun possibly, we should expect to see no difference in the pattern of eye movements for these two displays.

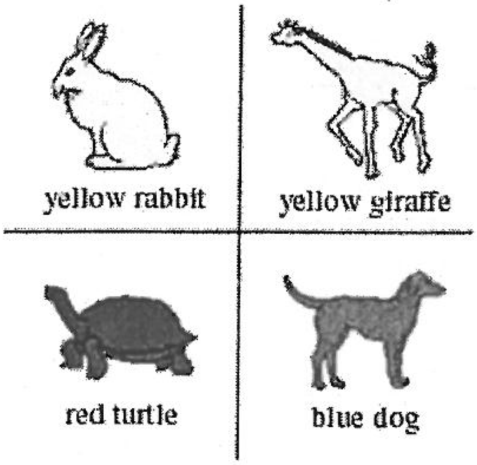


Figure 1. Unambiguous Condition.

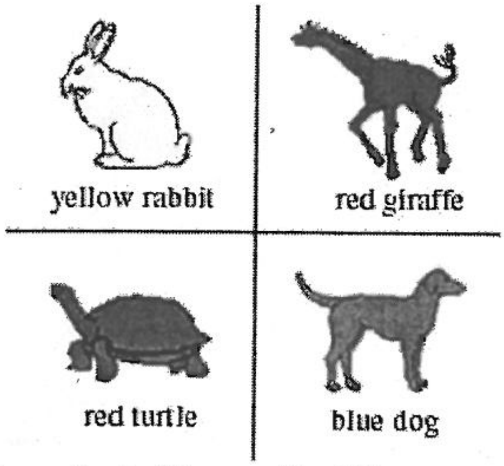


Figure 2. Ambiguous Condition.

The specific differences in the patterns of eye movements that we would expect to find under incremental processing are the following: 1) Eye movements to the target object should be delayed for the ambiguous condition, reflecting interference from the competitor object; and 2) There should be evidence of a greater number of looks to the competitor object in the ambiguous condition, compared to a baseline control in the unambiguous condition.

Previous studies with adults have indicated that both of these predictions are borne out (e.g. Eberhard et al., 1995). Specifically, the data from adults show that subjects typically initiate eye movements to the target sometime approximately 250 ms. after the end of the word at which it is possible to identify a unique target. When eye movements occur prior to this point, they tend to be distributed equally among objects whose properties are consistent with the information available from the speech stream to that point. This simple result has been replicated with displays and instructions that use a wide variety of properties and types of linguistic expressions, suggesting that it is not driven by specific expectations about the experimental instructions. In fact, this result has been the basis for numerous more elaborated manipulations involving higher-level discourse or conceptual knowledge (e.g. Sedivy, Tanenhaus, Chambers, & Carlson, 1999; Chambers, Tanenhaus, Eberhard, Carlson, & Filip, 1998).

We performed two variations of the same manipulation involving potential referential indeterminacy. One half of the studies involved instructions using prenominal adjectival modifiers, such as the example in Figures 1 and 2. The other half involved postnominal modification, where the disambiguating information came not from the head noun, but from a postnominal modifier, as in Figure 3, with the target instruction "Pick up the giraffe with stripes." This example was similarly compared to a condition in which the disambiguating information occurred earlier, in this case at the head noun (Figure 4).

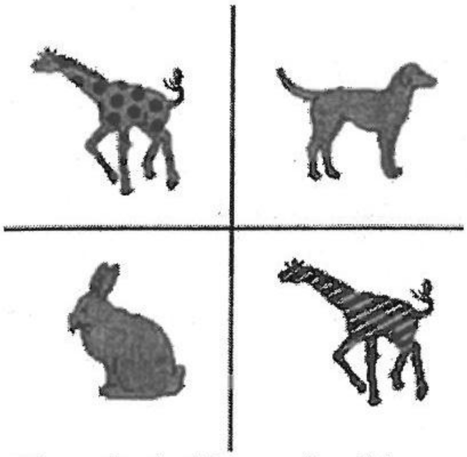


Figure 3. Ambiguous Condition.

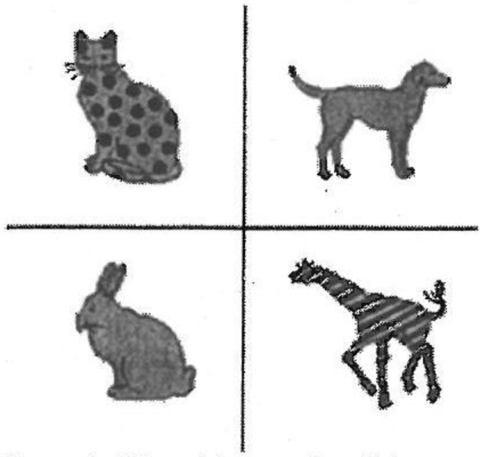


Figure 4. Unambiguous Condition.

This was done because one might imagine that if referential interpretation were delayed until the occurrence of the head noun, for instance, we might see different results for the displays with postnominal modifiers, where the disambiguating information comes after the head noun, as opposed to the prenominal modifiers, where the disambiguating information comes at the head noun itself. Thus, if referential interpretation did not occur until the head noun itself, we would expect to see that the manipulation of the display would result in differences for the postnominal modifiers displays, but not the prenominal modifiers displays.

Subjects were 11 children between the ages of 5 and 7 who were recruited through local schools and daycare centers, and brought to the eyetracking lab at Brown University by their parents. All of the children were native, monolingual speakers of English with normal vision and hearing, and with no history of language disorders. The subjects sat in front of a vertical board with four cardboard cards of colored line-drawings of animals fastened to the board with Velcro strips, and were told to pick up one of the cards and use it to mimic some action (e.g. "Pick up the red turtle, and make him kiss the blue dog"). Experimental stimuli were 20 spoken target instructions, read aloud by one of the experimenters. Half of the stimuli were accompanied by a display such as the one in Figure 1 (Unambiguous Condition) where the target object could be identified based on the information available at the point of the first content word of the noun phrase; the remaining half resembled Figure 2 in that the point of disambiguation occurred later (Ambiguous Condition). In addition, half of critical trials described the target object by means of a color adjective, and the other half described the target by means of a postnominal prepositional phrase encoding some marking on the object (e.g. "Pick up the rabbit with polka dots"). Each instruction occurred in both conditions, with minimal changes to the display to allow for either early or late disambiguation. Subjects heard each target instruction only once, with displays rotated such that half the subjects saw one of the possible displays, and the remaining half saw the second possible display. The animals were either red, blue, or yellow in color, or plain, with stripes, or with polka dots in marking. The objects in the display differed only along one dimension (i.e. either the objects were all plain, but of different colors, or they were of the same color, but with different markings). Each set of experimental trials was preceded by a set of four practice trials.

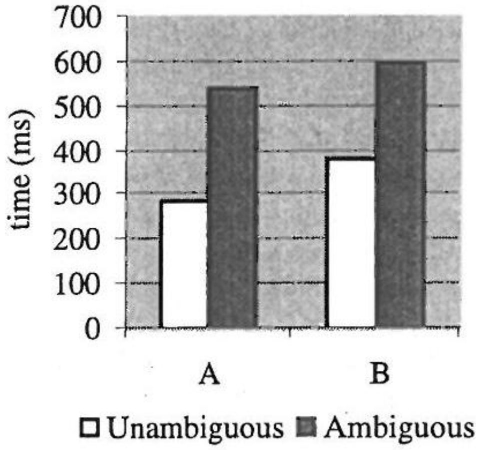
A colored star was placed in the center of the display board. Each trial began with a request for the subject to look at the star, so that eye movements to the target objects could be measured from a default position that was equidistant to all of the objects in the display.

While the subject followed the instructions, eye movement data were recorded using a lightweight ISCAN head-mounted video-based tracking system. The camera provided an infrared image of the eye at 60 Hz, and determined monocular eye position by monitoring the locations of the center of the pupil and the cornea reflection. A scene camera was mounted on the side of the headband, providing an image of the subject's field of view. Prior to the experimental task, a brief 5-point calibration routine was performed, with calibration carefully monitored throughout each trial. A VCR record was made for each experimental trial, consisting of the instructions spoken by the experimenter into a microphone, as well as the subject's moment-by-moment gaze fixation superimposed over the scene camera image.

3. Results and Discussion

Eye movement data were determined by analyzing the videotape and noting the frame at which an eye movement was initiated to the target object. The frame representing the onset of the last content word in the relevant noun phrase (e.g. *cat,* or *stripes*) was also noted. Eye movement latencies were computed by determining the time lapse between this critical point in the speech stream, and the initiation of the eye movement towards the target object (i.e. by noting the frame at which the fixation crossed boundaries of spatially defined scoring regions). These data include all first fixations to the target, regardless of whether they were preceded or followed by fixations to other objects. Mean latencies are shown in Figure 5. Since the pattern of results was identical for both pre-nominal and post-nominal modification, these conditions were collapsed for the purposes of statistical analysis.

A comparison of the eye movement latencies for the Unambiguous Condition (335 ms.) vs. the Ambiguous Condition (571 ms.) revealed a significant difference ($F(1,10) = 10.99$, $p<0.01$). Assuming that the time between the initial programming and execution of an eye movement is similar for children as it is for adults, this suggests that eye movements were being programmed approximately 350-400 ms. after the *onset* of the disambiguating word in the Ambiguous Condition, where the final word in the noun phrase is the earliest point where sufficient information is available in the speech stream to identify a target referent. These results suggest that children's eye movements are every bit as sensitive to information in the speech stream as adults (Eberhard et al., 1995).



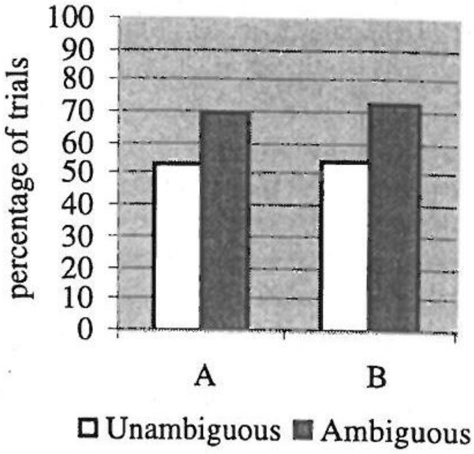


Figure 5. Latencies for first look to target. A: Pre-nominal modifier; B: Post-nominal modifier.

Figure 6. Percent trials including a look to a competitor object. A: Pre-nominal modifier; B: Post-nominal modifier.

An observable difference between the child data found in this study and the adult data from similar studies is that children are more likely to look at objects other than the target. Thus, adults, when presented with displays and instructions of comparable complexity, tend to look at the central fixation cross until after the point of disambiguation in the speech stream, and rarely look at other objects, children are making more frequent eye movements to the other objects. In fact, the pattern of eye movements exhibited by children in this study is similar to the behavior of adults in experimental contexts involving more complex displays (7 objects instead of 4), and more complex instructions (Eberhard et al., 1995), suggesting that perhaps children's memory limitations may require them to scan more extensively to extract information from the visual scenes. However, as with the child data reported here, the point of disambiguation manipulation yields robust differences for adults even with the more complex experimental materials.

In addition to latencies, the identity of objects other than the target is informative. Note that for the Ambiguous Condition, each display contained an object that shared the property denoted by the first content word in the noun phrase (e.g. *red* for *the red turtle* or *giraffe* for *the giraffe with stripes*), whereas the Unambiguous Condition contained no such "competitor" objects. As a coarse measure of whether children were more likely to look at the competitor objects than other nontarget objects, the proportion of trials which contained an eye movement to the competitor object for Ambiguous displays was calculated and compared to the proportion of trials containing eye movements to the unrelated object in the corresponding location in the Unambiguous Condition. Results are shown in Figure 6. Again, as there were no differences due to type of modification, the data were collapsed.

The proportion of trials containing looks to the competitor were found to be significantly different (72% vs. 55% respectively; $F(1,10) = 5.73$, $p<.05$). These data suggest that looks to nontarget objects are not random, but rather, reflect a process of continuously narrowing down a set of possible referents on the basis of partial information in the speech stream, such that referents that are in this set at some time prior to the point of disambiguation are activated above baseline levels.

These results show compelling evidence that children's language processing involves a process of continuously and quickly mapping linguistic expressions onto corresponding referents, showing similar time-course processing to adults. These data provide no evidence for a stage of processing where syntactic relations are computed, but not the semantic reflexes of those syntactic relations. In this aspect, children's processing appears to reflect much the same mechanism as seen in adults based on previous studies within the eyetracking paradigm, as well as Tyler & Marslen-Wilson's (1981) findings. More generally for the enterprise of the study of child language, the data suggest that the eye monitoring paradigm is sufficiently temporally sensitive to be used with children, even despite the noisier patterns of data that occur. This technique has proven to be extremely sensitive and useful in studies with adults ranging from investigations of word recognition to syntactic ambiguity resolution, to the incorporation of discourse pragmatic information in processing, suggesting a wide array of possible applications to the field of language acquisition.

4. Future Directions

The establishment of an on-line experimental paradigm that shows sensitivity to a variety of language processing phenomena and that can also be readily applied to research with young children is likely to prove an essential catalyst in stimulating research spanning the subdisciplines of language acquisition and processing. We conclude this paper by pointing to a range of recent or ongoing work that we believe is of particular relevance to such collaborations.

The first study we are aware of that directly investigates processes of syntactic ambiguity resolution in children is reported in Trueswell, Sekerina, & Hill (1999). The study uses the eye movement paradigm described in the current paper. Their results suggest that, unlike adults, children fail to use cues available in the referential context to avoid syntactic misanalysis of temporarily ambiguous sentences such as "Put the frog on the napkin into the box". In this study, children consistently interpreted the ambiguously attached prepositional phrase "on the napkin" as attached to the verb phrase, rather than as a nominal modifier, as shown by their eye movement patterns, and even coarser measures such as their ultimate actions in carrying out the instructions. Tanenhaus et al. (1995) reported that adults showed no evidence of such initial misanalysis when the visual display contained an array of objects that contextually supported the modifier interpretation (i.e. when two objects corresponding to the head noun were present, thereby motivating disambiguation by means of a postnominal modifier). The different patterns of results for adults and children raise a number of possible explanations. The difference could be indicative of different processing architectures implicated in syntactic processing, or may reflect differences in the knowledge representations that children have pertaining to either pragmatic properties of referential phrases, or different verb argument structure biases (the latter is explored in Trueswell, Sekerina, & Logrip, 1999). Further, the fact that children showed striking difficulty in recovering from the misanalysis has interesting implications for the nature of linguistic uptake of the input in acquisition. It raises the possibility that a substantial number of temporarily ambiguous sentences that are processed by adults with relative ease may ultimately be assigned no meaningful structure at all for children.

A second domain that promises to be of mutual interest to researchers in acquisition and processing pertains to studies of filler-gap relations in wh-constructions. Work in progress extends the eye monitoring technique to the processing of wh-questions by adults, and compares eye movement patterns in response to wh-questions vs. yes/no questions following a narrative in which relevant characters and entities are established. For instance, after a story in which a character named Jody squashes a spider with a shoe, subjects might hear "What did Jody squash the spider with?" or "Did Jody squash the spider with a shoe?" Subjects show evidence of initiating highly anticipatory eye movements to a picture of a spider in the display upon hearing the verb "squash" when hearing the wh-question, replicating findings from more traditional reading time methods that the processor attempts to identify and fill possible gap locations as quickly as possible (Stowe, 1986). Furthermore, this anticipation of gap locations appears to be contingent on transitivity information associated with the verb, indicating that there are strong local cues to gap locations (Sussman & Sedivy, in preparation). The possibility of conducting investigations into the processing of filler-gap relations with child populations raises several interesting questions. For instance, will children show similar sensitivity to verb argument structure, or is gap-filling guided by coarser representations? Do children show dramatically different verb-specific expectations from adults, and if so, what impact does it have on their ability to eventually arrive at the correct analysis of the sentence? Do children and adults show similar patterns of coordination of local constraints such as verb argument structure with more global syntactic constraints such as wh-island constraints, and what implications does this interaction have for children's acquisition of global syntactic constraints?

A third line of research that we are currently pursuing involves questions of how pronouns are interpreted where more than one antecedent is licensed by the grammar. There is evidence that pronoun resolution in adults is governed by principled pragmatic mechanisms (e.g. Gordon, Grosz, & Gilliom, 1993). We have preliminary corpus evidence suggesting that children's distributions of pronouns and referring expressions reflect similar constraints. It will be of interest to determine whether such constraints systematically guide or bias children's resolution of pronominal expressions, and whether these processing effects interact systematically with the acquisition of anaphoric expressions more generally.

These examples are simply points of departure. It is our hope that they will serve as beginning points for more intense and sustained cooperative efforts between researchers in language acquisition and sentence processing.

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