The structure-sensitivity of memory access: evidence from Mandarin Chinese

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Abstract

The present study examined the processing of the Mandarin Chinese long-distance reflexive *ziji* to evaluate the role that syntactic structure plays in the memory retrieval operations that support sentence comprehension. Using the multiple-response speed-accuracy tradeoff (MR-SAT) paradigm, we measured the speed with which comprehenders retrieve an antecedent for *ziji*. Our experimental materials contrasted sentences where *ziji*’s antecedent was in the local clause with sentences where *ziji*’s antecedent was in a distant clause. Time course results from MR-SAT suggest that *ziji* dependencies with syntactically distant antecedents are slower to process than syntactically local dependencies. To aid in interpreting the SAT data, we present a formal model of the antecedent retrieval process, and derive quantitative predictions about the time course of antecedent retrieval. The modeling results support the *Local Search hypothesis*: during syntactic retrieval, comprehenders initially limit memory search to the local syntactic domain. We argue that Local Search hypothesis has important implications for theories of locality effects in sentence comprehension. In particular, our results suggest that not all locality effects may be reduced to the effects of temporal decay and retrieval interference.
**Introduction**

One fundamental question for models of sentence comprehension is the question of how comprehenders are able to construct long-distance linguistic dependencies reliably and rapidly in comprehension. Long-distance dependencies occur whenever two non-adjacent elements in a sentence must be syntactically and/or semantically integrated with each other. For example, in a sentence like “William took a terrible yet interesting photo of himself”, the relationship between the reflexive anaphor *himself* and its antecedent *William* is constructed across multiple intervening words. Recent models of sentence comprehension have advanced the hypothesis that this sort of syntactic dependency formation minimally requires the use of memory retrieval mechanisms to access temporally distant syntactic encodings. On this view, to interpret the reflexive in the sentence above, comprehenders must retrieve a representation of the antecedent from memory. Moreover, it has been argued that the memory retrieval mechanisms that underlie sentence comprehension share a number of key features with domain-general retrieval mechanisms (Lewis & Vasishth, 2005; Lewis, Vasishth & Van Dyke, 2006; McElree, 2000; McElree, Foraker & Dyer, 2003; Van Dyke & Lewis, 2003). This view receives support from mounting evidence that comprehenders rely on a cue-based, direct access retrieval mechanism during syntactic comprehension. Cue-based retrieval mechanisms allow direct access to syntactic encodings by matching retrieval cues to the features of all item representations in memory in a parallel fashion. Items whose features provide a close match to the retrieval cues are then retrieved for further processing (for a discussion of implementations of this idea, see Clark & Gronlund, 1996).

Despite the growing evidence in favor of cue-based retrieval in sentence comprehension, these models still face a number of difficult theoretical questions. One central question concerns the nature of the retrieval cues used to retrieve syntactic dependents during processing (Dillon, Mishler, Sloggett & Phillips, 2013; Kush, 2013; Van Dyke & McElree, 2011). Existing evidence suggests that comprehenders use both semantic and syntactic cues to guide retrieval (Van Dyke, 2007; Van Dyke & McElree, 2006, 2011). Furthermore, there is some evidence that syntactic cues may be given priority over semantic or morphological cues, although this may depend on the kind of dependency being formed (Dillon et al., 2013; Van Dyke & McElree, 2011). However, very little is known about the nature of the syntactic cues that guide retrieval operations. In the present paper, we address this question by asking whether syntactic cues refer only to the attributes of individual syntactic encodings, such as their case or thematic role (*item information*), or whether syntactic cues distinguish constituents based on their hierarchical or linear distance from the retrieval site (*position information*). We hypothesize that the cues that guide memory retrieval during parsing do include
positional syntactic information, and furthermore, that comprehenders use positional information as retrieval cues to prioritize retrieval of constituents within the local syntactic domain (the Local Search hypothesis).

The goal of the present paper is to evaluate the Local Search hypothesis by examining the speed with which comprehenders process reflexive dependencies in Mandarin Chinese, where reflexive anaphors may be bound either inside or outside of their local clause. We then develop a formal model of a local search retrieval process, and derive quantitative predictions about the processing time necessary to recover ziji’s antecedent if the parser assumes a local search strategy. To preview our conclusion, the results of our investigation support the main predictions of the Local Search hypothesis. We argue that the Local Search hypothesis offers important insight into a widely-observed preference for local dependencies over distant dependencies in sentence comprehension (Bartek, Lewis, Vasishth & Smith, 2011; Gibson, 1998; Hawkins, 1994; Kimball, 1973; a.o.). In particular, the results presented here support theories that attribute these locality effects to a substantive bias to search syntactically local domains at retrieval, rather than theories that attribute locality effects entirely to effects of decay or interference of items in working memory (Lewis & Vasishth, 2005; Lewis et al., 2006; MacDonald, Pearlmutter & Seidenburg, 1994).

Cue-based retrieval in sentence processing

There are two main sources of empirical evidence that implicate the use of a cue-based retrieval mechanism in parsing. The first source of evidence comes from studies of interference effects in online processing. In a cue-based, direct access memory architecture, the process of matching the retrieval cues against all memory encodings allows rapid access to task-relevant encodings, but is susceptible to interference effects. If there is a good match between the retrieval cues and more than one item in memory, then access to the target memory can be impeded. Similarity-based interference effects have been widely documented in studies of sentence comprehension (Drenhaus, Frisch, & Saddy, 2005; Gordon, Hendrick & Johnson, 2001, 2004; Lewis & Vasishth, 2005; Lewis et al., 2006; Van Dyke, 2007; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2006, 2011). In addition, cue-based retrieval architectures naturally account for the phenomenon of illusory licensing. Illusory licensing occurs when comprehenders appear to use a grammatically unavailable constituent to license a syntactically dependent element (negative polarity item licensing: Vasishth, Brussow, Drenhaus & Lewis, 2008; Xiang, Dillon & Phillips, 2009; subject-verb agreement: Dillon et al, 2013; Wagers, Lau & Phillips, 2009). In a cue-based retrieval architecture, this arises because a syntactically illicit constituent may be misretrieved during the search for a licensor, which in turn leads to illusory licensing of the dependent element that triggered the retrieval.

A second important line of evidence in favor of cue-based retrieval mechanisms
comes from studies of the time course of memory access. In a cue-based, direct access memory architecture, only items that match the retrieval cues are contacted at retrieval, and so retrieval times are predicted to be constant over search sets of different sizes. This prediction has been supported by speed-accuracy tradeoff studies (SAT) of item recognition. In an SAT study, participants are trained to respond at a number of varying response deadlines. This allows the experimenter to derive an SAT function that tracks behavioral accuracy as a function of time. This function measures the complete time course of information processing. Importantly, SAT permits the experimenter to make separate measurements of processing speed and accuracy, two aspects of information processing that are confounded in simple reaction time (RT) paradigms (Wickelgren, 1977). SAT studies of recognition judgments in list memory tasks have provided support for direct access models of recognition memory by showing that the number of elements in the list does not effect processing speed (McElree & Dosher, 1989). This finding is not consistent with search models, which retrieve representations based on their location in memory. Search may proceed either in serial or parallel, but it crucially involves performing explicit comparison processes over a positionally defined search set (see Townsend & Ashby, 1983). For this reason, search models predict that memory access times should grow either as a function of the size of the search space, or as a function of the position of the target in a serial or ordered search. This prediction reflects the fact that the more sampling operations are necessary to recover the intended target, the longer time should be required for retrieval. In contrast to item recognition, the retrieval of explicit order information does appear to recruit this sort of iterative search process (Gronlund, Edwards & Ohrt, 1997; McElree & Dosher, 1993).

In language comprehension, research using the SAT technique has demonstrated that memory access time does not grow with the size of the search space (Foraker & McElree, 2007; Martin & McElree, 2008, 2009; McElree, 2000; McElree et al., 2003). For instance, McElree et al. (2003) examined the processing of object cleft-constructions as in (1), in which the clefted object is separated from the associated verb by 1, 2, or 3 clauses:

(1) a. It was the scandal that the celebrity relished.
   b. It was the scandal that model believed that the celebrity relished.
   c. It was the scandal that the model believed that the journalist reported that the celebrity relished.

McElree and colleagues used the SAT paradigm to measure comprehension accuracy at various time points from the offset of the final verb in (1), manipulating the hierarchical (and linear) distance between the filler (the scandal) and the verb that hosts its gap (relished). The results suggested that the length manipulation impacted how accurately comprehenders were able to retrieve the wh-filler, as reflected in terminal
sensitivity values, but that it did not impact the speed of this retrieval. McElree et al. argued that these results favor a cue-based direct access retrieval mechanism over search-based retrieval mechanisms, on the assumption that their length manipulation increased the size of the search set for the critical retrieval of the wh-filler. Similar results were observed for the comprehension of verb phrase ellipsis (Martin & McElree, 2008, 2009), sluicing (Martin & McElree, 2011), and pronominal reference (Foraker & McElree, 2007).

Although previous SAT studies have consistently found that the structural distance between two elements in a dependency does not impact the speed of forming the dependency, the technique has been shown to have the power to detect other sorts of processing slowdowns that occur during sentence comprehension. For example, SAT studies have shown that processing slowdowns obtain in cases of syntactic reanalysis (Bornkessel, McElree, Schlesewsky & Friederici, 2004; McElree et al, 2003), cases of potential lexical ambiguity (Foraker & McElree, 2007), and configurations that require multiple retrieval operations (McElree et al., 2003). McElree et al. (2003) also reported that retrieval speed is slowed by interpolating a relative clause between a subject head noun and its dependent verb (see also Wagers & McElree, 2009).

Locality effects in a cue-based architecture

The adoption of a cue-based, direct access architecture for syntactic processing requires a reexamination of existing theories of locality effects in sentence processing. It is widely observed that local syntactic dependencies are easier to process or, in cases of ambiguity, preferred over longer syntactic dependencies (Bartek et al., 2011; Frazier, 1978; Gibson, 1998; Hawkins, 1994; Just & Carpenter, 1992; Kimball, 1973; Lewis & Vaisishth, 2005; Lewis et al., 2006; inter alia). Because cue-based, direct access mechanisms do not need to execute a serial search of a parse to retrieve a syntactic dependent or a pronominal antecedent, locality effects cannot emerge as a property of the access mechanism without making further assumptions. Instead, the advantage for local dependencies reflects two factors: time-based decay and interference processes (Bartek et al., 2011; Lewis & Vaisishth, 2005; Lewis et al., 2006; Van Dyke & Lewis, 2003; see also Frazier & Clifton, 1998). Decay and interference both serve to degrade the availability of more distant syntactic constituents, thus making processing of more distant dependencies more difficult. Decay does so by affecting the activation of constituents: more local constituents will have higher activation values by virtue of being accessed more recently. The effect of interference is more indirect. When dependencies are longer, then there are likely to be more constituent encodings in memory. When there are more items in memory, the degree of similarity-based interference is likely to be greater.

These explanations for locality effects in sentence processing stand in contrast to the explanation offered by accounts that attribute locality effects to a parsing strategy that
prioritizes the retrieval of constituents within some local syntactic domain over those in more distant syntactic domains (Berwick & Weinberg, 1984; Frazier, 1978; Frazier & Clifton, 1989, 1996; Gibson, 1998; Gibson, Pearlmutter, Canseco-Gonzalez & Hickok, 1996; Kimball, 1973; Sturt, Pickering & Crocker 1999, 2000). Although these accounts vary widely in their details, they might all be called search-based accounts of syntactic retrieval. The core claims of search-based accounts include i) the parser distinguishes local versus distant syntactic domains through positional syntactic information, and ii) the retrieval of a potential syntactic dependent proceeds by first searching within some local syntactic domain, the size of which may vary across theories.

Although it may appear that the claims of these search-based accounts are incompatible the locality account advanced by cue-based parsing models, this is not so. The core claims of search-based accounts may in fact be integrated with cue-based retrieval models if we suppose that positional syntactic information is available to guide retrieval operations, and that at retrieval the parser uses this positional information to limit retrieval to a local syntactic domain. We call this the Local Search hypothesis:

(2) **Local Search hypothesis**: The parser uses positional syntactic information during the retrieval of syntactic dependents, and positional cues serve to restrict retrieval to constituents in some local syntactic domain.

According to the Local Search hypothesis, locality effects in sentence processing reflect in part a parsing strategy that prioritizes the retrieval of syntactically local constituents. In other words, locality effects do not merely emerge from effects of decay and interference, but instead they reflect a strategy for memory retrieval.

Within existing cue-based parsing models, it is not generally assumed that positional syntactic information is available to guide retrieval. Lewis and Vasishth (2005) propose that positional syntactic information, either hierarchical or linear, plays no role in the memory retrieval operations that guide attachment operations (c.f. the no serial order hypothesis; see also Lewis et al 2006). For example, while the parser may be able to use item information such as case to identify the subject of a sentence, it cannot use positional syntactic information to distinguish the encoding of the local subject from a more distant subject. On this account, the inability to distinguish distant and local subjects on the basis of their syntactic position provides an explanation of the well-known center embedding difficulty in terms of retrieval difficulty: when the parser needs to retrieve a subject for an embedded verb, there are too many similar subject encodings in memory to permit the parser to retrieve the grammatically appropriate subject, and positional information cannot be recruited to help with this process (Lewis & Vasishth, 2005; Lewis et al, 2006). In contrast to the Local Search hypothesis, these models claim that locality effects in sentence processing are entirely reducible to the effects of interference and temporal decay.
This claim is compatible with the SAT results reviewed above, which suggest that neither the linear nor structural position of the retrieval target directly impacts retrieval times. It is tempting to conclude from this that positional syntactic information is not used to guide syntactic retrieval operations. However, this conclusion would be premature on the basis of these data alone. These studies largely investigated configurations where there was only one grammatically licit position that could serve as the target of the retrieval. For instance, when the verb initiates the retrieval for the clefted object filler in (1), *wh*-feature cues could unambiguously select the filler as the target of retrieval. For this reason, they provide no direct test of whether syntactic position information plays a role in helping the retrieval mechanism to distinguish between multiple, syntactically accessible targets in different syntactic domains.

A potential exception is Martin and McElree (2011), who investigated the processing of sluiced sentences as in (3):

(3)  

a. Distant VP: Michael drank coffee and typed something, but he didn’t tell me *what*.  
b. Recent VP: Michael typed something and drank coffee, but he didn’t tell me *what*.

Martin and McElree hypothesized that the processing of the sluiced *wh*-phrase *what* requires comprehenders to retrieve an antecedent VP from memory, which is then used to construct the elided clause (i.e. the IP) at the sluice site. Martin and McElree manipulated the distance between the antecedent transitive VP (*studied* in (3)) and the sluiced *wh*-phrase. In addition, they attempted to manipulate the size of the antecedent search set by manipulating whether a competitor VP was present in a coordination structure (*slept* in (3)). Nonetheless, they observed that only accuracy, not processing speed, was negatively impacted by the presence of multiple VP antecedents. They additionally observed that recency of the antecedent VP only impacted retrieval accuracy. They argued that this pattern of results provided a strong data point in favor of content-addressable retrieval operations over syntactically structured search operations. However, because the two candidate antecedents were coordinated, this study may not have effectively manipulated the syntactic locality of the antecedent VP. Both potential antecedents were in a structurally similar position in the preceding clause. For this reason, this study leaves unresolved the question of how structural locality impacts retrieval.

The current study

In the present study we evaluated the Local Search hypothesis by investigating the processing of the Mandarin Chinese long-distance reflexive *ziji*. The anaphor *ziji* is an
example of the cross-linguistically well-attested class of long-distance reflexives, reflexive pronouns that may be bound outside of their local clause. Thus, unlike the English reflexives himself and herself, ziji does not require that its antecedent be in the same clause, as seen in (4), where subscript indices are used to indicate possible coreference:

(4)  
\[ \text{Zhangsan}_i \text{ shuo } \text{Lisi}_i \text{ nongshang-le } \text{ziji}_{ij} \]
Zhangsan says Lisi harm-PERF self
“Zhangsan says that Lisi harmed him / herself”

In (4), it can be seen that ziji may be bound either by the local subject Lisi or the matrix subject Zhangsan. Like many long-distance reflexives, ziji imposes a number of constraints on potential linguistic antecedents (Büring, 2005; Huang, Li & Li, 2009). There are significant syntactic constraints placed on antecedents: they must be subjects whose clausal projection dominates the clause that contains ziji (Huang & Liu, 2001). In addition to these syntactic constraints, there are a number of discourse-pragmatic constraints on the use of ziji. Antecedents must be animate and sentient, and must be prominent in the current discourse (Huang & Liu, 2001; Xue, Pollard & Sag, 1994). In the absence of an appropriate antecedent in the immediate sentential context, ziji has been claimed to refer to the speaker, presumably as a reflex of the prominent discourse status that is automatically afforded to the speaker (Huang & Liu, 2001; Kuno, 1972). Though there are ongoing debates about the exact nature of ziji’s licensing conditions (Huang, Cole & Hermon, 2006), it is uncontroversial that resolving the antecedent-anaphor dependency requires the comprehender to systematically exclude structurally unacceptable referents from consideration.

We take the embedded and matrix clauses in (4) to constitute distinct syntactic domains for the purposes of finding ziji’s antecedent. On this assumption, we may evaluate the Local Search hypothesis by investigating the processing of local and long-distance interpretations of of ziji as in (5):

(5)  
\[ (a) \text{ Zhangsan}_i \text{ shuo } \text{fengbao}_j \text{ hai-le } \text{ziji}_{ij} \]
Zhangsan says storm harm-PERF ziji
“Zhangsan said the storm harmed him.”

\[ (b) \text{ Xiaoshuo}_i \text{ shuo } \text{Zhangsan}_j \text{ hai-le } \text{ziji}_{ij} \]
novel says Zhangsan harm-PERF ziji
“The novel said Zhangsan harmed himself.”

Because ziji requires an animate and sentient antecedent, only Zhangsan in (5a,b) is a grammatically licensed antecedent. Of critical interest is the long-distance configuration (5a), where the local subject is inanimate and thus semantically
inappropriate as an antecedent for ziji. The critical empirical question in this comparison is whether comprehenders will show delayed access to the matrix antecedent in (5a). If the match on semantic cues outweighs the effect of dependency locality, and if it grants reliable direct access to the matrix antecedent, then the only difference between (5a) and (5b) should be the amount of time the antecedent has decayed in memory. Previous findings show that decay alone does not impact the speed of retrieval (see e.g. McElree et al. 2003). Thus, if semantic cue match outweighs the effect of locality in this configuration, we predict no difference in retrieval speeds between local and long-distance interpretations of ziji.

The Local Search hypothesis, however, does predict a difference in retrieval speeds. If the parser initially uses cues that limit retrieval to the local clausal domain, then on a significant portion of trials the comprehender should misretrieve the local subject in (5a) despite its poor fit to ziji’s semantic cues. This would require the comprehender to engage costly reanalysis processes to recover the more distant antecedent, leading to slowed retrieval times in (5a). In Experiment 1, we used a variant of the SAT technique known as multiple response SAT (MR-SAT) to estimate the speed of processing ziji in these two configurations to determine whether local and long-distance ziji dependencies are associated with different retrieval speeds.

**Experiment 1**

Experiment 1 employed the multiple-response speed-accuracy tradeoff procedure (MR-SAT; Wickelgren, Corbett & Dosher, 1980) to estimate the time course of retrieving an antecedent for ziji in sentences such as (5). MR-SAT is an attractive technique to use in studying language comprehension because it dissociates processing speed from processing accuracy (McElree 2000; McElree et al 2003; Foraker & McElree 2007; Martin & McElree 2008, 2009, 2011). In a MR-SAT paradigm, participants are required to make acceptability judgments at pre-specified response latencies. This provides a measure of how accuracy grows over time, and thus provides a direct measure of the time course of processing. In contrast, single reaction time paradigms are limited in how informative they are about time course of processing. Because participants can trade speed and accuracy in many standard judgment tasks (Wickelgren, 1977), merely estimating a point reaction time per condition (or a single RT/accuracy pair) can obscure differences between the probability of successfully completing a process and the speed with which that process reaches completion. In contrast, the full time course summarized in an SAT function allows us to separately estimate the speed and the accuracy of memory retrieval. In the present case, we are concerned with the nature of any difficulty observed with non-local ziji interpretations as in (5a). Prior work suggests that retrieval difficulty associated with temporal decay or linear distance is associated with a decrease in retrieval accuracy, rather than retrieval speed (McElree 2000; McElree et al 2003;
Based on these results, we do not expect to observe differences in retrieval speed purely as a function of decay or recency.

**Method**

**Participants**

Twenty college students from Beijing Normal University participated in the experiment. Data from 2 participants were excluded due to atypical (sigmoidal) SAT curves, and the data from a further participant was excluded due to poor accuracy. The remaining 17 participants included 10 females, and had a mean age of 23.5 years. Each participant completed six 1-hour experimental sessions spaced at least a day apart, in addition to a 1-hour practice session for familiarization with the MR-SAT procedure. All participants were native Mandarin Chinese speakers and had normal or corrected-to-normal vision. They were paid 35 RMB per hour for their participation in the experiment.

**Materials**

Our critical experimental materials were Mandarin sentences that contained a main clause verb that selects for a sentential complement. The embedded complement clause was always transitive. Two features of the stimuli were manipulated. One was the position of a syntactically prominent animate subject; it was either the subject of the main clause, the subject of the local (embedded) clause, or not present. In addition we manipulated the form of the embedded object NP, which was either the long-distance reflexive zìjì, a plausible definite NP, or an implausible definite NP. In all conditions, the embedded object was always the sentence-final word. The acceptable definite NP object sentences formed control conditions to ensure that any differences observed for zìjì were specific to retrieval processes associated with anaphoric expressions. Unacceptable control conditions were also included. The inclusion of these control conditions minimized the predictability of the sentence-final object, and so within the experiment neither the presence of zìjì nor the acceptability of the continuation was predictable from the sentence context.

This design provided three critical reflexive conditions designed to investigate the processing of zìjì (conditions 1-3 in Table 1). Based on the position of the animate subject, zìjì either took a long-distance antecedent (LD antecedent condition; 1), a local antecedent (Local antecedent condition; 2), or had no antecedent in the sentence (No antecedent condition; 3). The well-formed control conditions replaced zìjì with a full NP that was a plausible object of the embedded verb (e.g., the batsman in conditions 4-6); whereas the unacceptable control conditions replaced zìjì with a full NP that was an
implausible object of the embedded verb (e.g., glasses in conditions 7-9), resulting in a semantic anomaly. The primary experimental contrast was the effect of the position of the animate subject on the speed and accuracy of processing sentences that contained ziji (conditions 1-2) and sentences that contained acceptable definite NP objects (conditions 4-5).

Additionally, to increase the difficulty of the task, a temporal adverbial clause was interpolated between the embedded subject and the embedded verb. In all conditions, an animate NP was used as the subject of the temporal adverbial phrase. However, since it occupied a position that is not structurally higher than ziji, it is not a grammatical antecedent for ziji. In the local ziji and the corresponding control conditions, the main clause subject NP was always an inanimate noun that described a form of written or spoken media (e.g. book, documentary, memo) to ensure compatibility with the meaning of the main clause verbs (e.g., say) while being an unacceptable antecedent of ziji. None of the inanimates used in any position could be construed metonymically; metonymic interpretations of inanimates (i.e. the newspaper being used to refer to the employees of the newspaper) may be used as antecedents for ziji.

Forty sets of the 9 sentence types (5 acceptable and 4 unacceptable) were generated. The 360 sentences were equally distributed in 6 presentation lists, one for each of the 6 sessions, to minimize the repetition of content material within a session. Crucially, no two instances of ziji sentences (conditions 1-3) from the same set were included in a single presentation list. Within a session, each participant viewed 206 sentences, of which 60 were drawn from the current study. Each participant saw all 9 versions of each item set across the six experimental sessions. Since only one third of target sentences contained ziji, the critical ziji conditions comprised around 10% of all sentences within and across sessions. The order of presentation within a session was randomized.

Procedure

Stimulus presentation, timing, and response collection were all carried out on a personal computer using the Linger software (Rohde, 2003). Each trial began with a 500 ms fixation cross presented in the center of the screen. Each word appeared in the center of the screen for 400 ms, followed by 200 ms of blank screen. All words were presented using simplified Chinese characters, and the last word of each sentence was marked with a period (•). At the onset of the final word, a series of 18 auditory response cues (50 ms, 1000 Hz tone) was initiated. The cues occurred every 350 ms, and the final word of the sentence remained on the screen. Participants were asked to decide for each sentence whether it was an acceptable, coherent sounding sentence or not (in Mandarin: tōngshùn héshì). Participants were trained to initially respond by pressing both response keys simultaneously to indicate an undecided response, and to respond at every tone. They
were then trained to switch their response to either the ‘accept’ or ‘reject’ key as soon as they could. Importantly, they were also trained to modify their responses if their assessment changed. During the 1-hour practice session, participants were told that some of the sentences were complex, but nevertheless were meaningful sentences, and explicit feedback was given about acceptable and unacceptable sentences in the experiment. Each participant performed six 1-hour experimental sessions, and in each they saw one of the lists of materials. The order of lists was randomized across participants.

Data Analysis

To derive the full time-course information, $d'$ scores were calculated by comparing an acceptable and an unacceptable condition at each of the response tones. The resultant series of $d'$ values at each time point $t$ was fit using a shifted exponential function:

$$d' = \lambda \left(1 - e^{-\beta(t-\delta)}\right), \quad t > \delta,$$

$$d' = 0, \quad \text{otherwise}$$

The SAT function in (6) describes the growth of discriminative accuracy over time using three parameters: asymptote ($\lambda$), rate ($\beta$), and intercept ($\delta$). Figure 1 presents a hypothetical SAT function that tracks the time course of growth in accuracy (in $d'$ units) over time. By regressing the non-linear SAT function against the time course data collected in the experiment, we may make inferences about the effect of experimental manipulations on each of the parameters. The initial period of chance performance is described by the intercept parameter ($\delta$), which indicates the point at which the SAT function departs from chance performance (0 in $d'$ units). The next portion of the function is characterized by a period of increasing accuracy; the rate of growth in this portion of the SAT function is described by the rate parameter ($\beta$). The last portion of the function reflects terminal accuracy in the behavioral judgment, and it is reflected in the asymptote parameter of the SAT function ($\lambda$). The intercept and the rate together index the speed of the decision process, while the asymptote indexes the terminal accuracy of the process. The processing speed may also be evaluated by considering a composite measure known as the speed of the SAT function ($\beta^{-1} + \delta$). By parameterizing the SAT function in this way, we can separately estimate the speed of processing (as reflected in the intercept, rate, or speed measures) and the accuracy of processing (as reflected in the asymptote). Differences in the intercept or rate parameters indicate a difference in processing speed between two conditions; differences in the asymptote parameter indicate a difference in processing accuracy.

$d'$ is the standard measure of discrimination (assuming equal-variance Gaussian distributions): $d' = \Phi(\text{hits}) - \Phi(\text{false alarms})$ (Macmillan & Creelman, 2004; $\Phi$ represents the inverse of the cumulative distribution function of the standard normal). However, in
the models reported below, we only report a pseudo $d'$ measure that does not correct for the false alarm rate ($d' = \Phi(\text{hits})$). We present an analysis of these transformed hit rates for the critical ziji conditions (Conditions 1 and 2) as well the LD and local control conditions (Conditions 4 and 5). We adopted this analysis because the somewhat high acceptability of the no antecedent condition (see below) made it inappropriate for the construction of a discriminative $d'$ measure. It is important to note that our pseudo $d'$ measure does not correct for any response bias that participants may have, and in this respect, our analysis differs significantly from the approach adopted in previous SAT work. However, we note that our critical conditions constitute a $2 \times 2$ crossed factorial design (presence of ziji by position of animate antecedent). This design allows us to account for any response bias introduced by two major features of our stimuli: the configuration of the sentence prior to the critical final word, and the presence of ziji in final position. If response bias varies as a function of the sentence context, then this bias should be shared by both ziji and control conditions. Likewise, if there is response bias associated with a sentence final ziji, as opposed to a sentence final lexical NP, then this bias should be shared by both ziji conditions.

Data analysis proceeded in two steps: a model selection analysis and a parameter estimation analysis (Liu & Smith, 2009). In the model selection analysis, the best fit SAT model was determined using the adjusted $R^2$-statistic (in (7)) using a hierarchical model-testing scheme over the averaged and individual data, an approach pursued in prior work on SAT in sentence comprehension (Foraker & McElree, 2007; Martin & McElree 2008, 2009; McElree, 2000; McElree et al., 2003). However, we note that for multiple-response SAT, determining the number of independent data points $n$ is not a trivial problem, because of the lack of independence between responses on any trial. Because of the uncertainty over the number of truly independent data points that underlie any one MR-SAT function, it is difficult to straightforwardly apply model fitting metrics such as adjusted $R^2$, the AIC, and the BIC. In the parameter estimation analyses, only fully saturated models that allow all parameters to vary by condition are considered, and any differences between the critical conditions on the parameters of interest are assessed using familiar hypothesis testing measures over individual parameter estimates. This analysis follows the recommendations of Lorch and Myers (1990) for dealing with regression analyses in the context of a repeated measures experiment. In order to obtain parameter estimates, we used the R statistical computing environment to fit non-linear regressions of the SAT function (6) against the $d'$ score (see Martin & McElree, 2008, 2009, 2011; McElree, 2000; McElree & Griffith, 1998; McElree et al., 2003). We used the nls() function with an adaptive non-linear least squares algorithm (Dennis, Gay & Welsch, 1981) to determine the least squares fit of the SAT function to the data.
Prior to modeling the \( d' \) scores, analysis was performed on empirical pseudo \( d' \) measures by participants. This was obtained by taking the average rate of acceptance over the last four response points in each condition to determine the empirical hit rate, and calculating \( d' \) as described above. Hit rates that reflected perfect performance were smoothed by subtracting 0.0125 from the hit rate (1/(2N) smoothing; Macmillan & Creelman, 2004).

Where appropriate, behavioral measures and parameter estimates from the SAT function in (6) were further analyzed by entering them into a 2 \( \times \) 2 repeated-measures ANOVA crossing dependency type (\( ziji \) vs. control) and the position of the animate argument (\( long-distance \) vs. \( local \)).

Of the twenty participants run, data from two participants were excluded due to unreliable dynamics estimates. The empirical \( d' \) scores from these participants appeared better fit by a sigmoidal rather than exponential function, leading to unrealistically large and unreliable differences in the critical conditions in the crucial intercept and rate parameters when fit with the SAT function in (6). The data from one further participant were rejected due to lower than 60% correct responses on both critical \( ziji \) conditions (1-2). These participants’ empirical \( d' \) were not included in any analyses below.

Results

Accuracy and empirical \( d' \) analysis

Average acceptance was 87% for long-distance \( ziji \) conditions, 83% for local \( ziji \) conditions, and 47% percent for no antecedent \( ziji \) conditions. The rates of acceptance for the corresponding control conditions were 91%, 88%, and 92%, respectively. The unacceptable control conditions each had an average acceptance rate of 2%. The relatively high rate of acceptance for the \( no \) \( antecedent \) \( ziji \) condition was unexpected. Because of the high rate of acceptance of this condition, we chose not to use it in \( d' \) scaling; instead, as described above, we employed a transformed hit rate for all SAT modeling. We take up the question of why the \( no \) \( antecedent \) \( ziji \) conditions were so frequently accepted in the discussion.

Table 2 presents the mean empirical pseudo \( d' \) for \( ziji \) and acceptable control conditions. The data were analyzed using a 2 \( \times \) 2 repeated-measures ANOVA with dependency type and animate position as within-participant factors. This analysis revealed a marginal main effect of position of animate argument \( (F(1,16) = 3.6, p < .08) \),
as well as a marginal effect of dependency type ($F(1,16) = 4.3, p < .06$). The interaction of animate position and dependency type was not significant ($F < .1$). However, planned comparisons between the long-distance and local conditions within zi ji and control conditions did not reveal any reliable effects ($zi ji$: $t(16) = 1.02, p = .32$; control: $t(16) = 1.6, p = .12$).

**Time course analysis**

Competitive fits of the shifted exponential function in (6) were conducted to assess differences in asymptotic accuracy, rate, and intercept across conditions for each participant. Model fits were conducted separately for control and zi ji conditions. Because the empirical $d'$ analysis revealed only marginal differences between conditions in accuracy, it is not clear whether competitive model fits are justified in allowing the asymptote parameter to vary freely between conditions. In light of this, we fitted two SAT functions to each data set: one model whose asymptote parameter was fixed to the empirical pseudo $d'$ obtained by averaging over the final four response latencies, and one where the asymptote parameter was allowed to vary. We report parameter estimates from the free parameter models, although we report inferential statistics for both free and fixed asymptote models.

Model-fitting analyses pitted nested models against each other on adjusted $R^2$ (7), following McElree et al. (2003) and Liu and Smith (2009). Fits to the across-participants average for the critical zi ji conditions revealed a small advantage for a model that allocated separate rate parameters ($\beta$) for local and long-distance conditions (fixed $2\lambda - 2\beta - 1\delta$, $R^2$: .983) compared to models that did not posit separate rate parameters for each condition (fixed $2\lambda - 1\beta - 1\delta$, $R^2$: .975; fixed $2\lambda - 1\beta - 2\delta$, $R^2$: .979). This difference reflected a small rate advantage for local zi ji condition over long-distance zi ji condition (Local $\beta$: 1.07 s$^{-1}$; LD $\beta$: 1.46 s$^{-1}$). For models with free asymptotes, the model that assigned separate rate parameters to local and LD zi ji conditions was also the highest on the adjusted $R^2$ metric (free $2\lambda - 2\beta - 1\delta$, $R^2$: .986). For free asymptote models, all models that assigned separate asymptotes to local and LD zi ji conditions received higher $R^2$ scores than corresponding models with a single asymptote parameter. Control conditions showed no improvement in fit for additional rate or intercept parameters (fixed $2\lambda - 2\beta - 1\delta$, $R^2$: .994; fixed $2\lambda - 1\beta - 1\delta$, $R^2$: .994). The same pattern was observed for models with free asymptotes. The average data for zi ji and control conditions, along with best-fit models on the adjusted $R^2$ metric, are presented in Figure 2.

Of critical interest is whether the fits to the average data reflect a reliable trend across individuals. It is possible that the SAT function reflected in the average is not in fact representative of a pattern observed in any individual subject (Liu & Smith, 2009), and in the present case, there was a very small difference between models with different dynamics parameters and those without. In order to assess the reliability of parameter
estimates across participants, each individual’s $d'$ data for each of the four critical conditions were fit with the SAT function, allowing estimation of individual parameter values. Fits were conducted both with fixed and free asymptote parameters. The results of this analysis for the critical $ziji$ conditions are presented in Table 3.

The individual parameter estimates were entered into a 2 × 2 repeated-measures ANOVA with dependency type and animate position as within-participant factors. ANOVAs revealed an interaction of dependency type and animate position both for rate parameters $\beta$ (free $F(1,16) = 4.8, p < 0.05$; fixed $F(1,16) = 1.5, p = .23$) and for the composite speed measure $\beta^{-1} + \delta$ (free $F(1,16) = 8.2, p < 0.05$; fixed $F(1,16) = 8.7, p < 0.01$). In addition, there was a main effect of dependency type on speed measures (free $F(1,16) = 6.1, p < 0.05$; fixed $F(1,16) = 5.7, p < 0.05$) and on rate parameters (free $F(1,16) = 3.6, p < 0.08$; fixed $F(1,16) = 6.2, p < 0.05$), reflecting faster processing of $ziji$ conditions. Additionally, for free asymptote models, a significant effect of dependency type was observed for the asymptote parameter $\lambda$ (free $F(1,16) = 4.9, p < 0.05$; fixed $F(1,16) = 4.3, p < 0.06$). There were no significant effects on the intercept parameter $\delta$ for either fixed or free asymptote models.

Planned pairwise comparisons revealed that these interactions were driven by differences in the $ziji$ conditions in the speed measure $\beta^{-1} + \delta$ (free $t(16) = -2.6, p < .05$; fixed $t(16) = -2.9, p < .05$). This analysis revealed only marginal effects on the rate parameter $\beta$ (free $t(16) = 1.9, p < .08$; fixed $t(16) = 1.2, p = .24$). There were no effects of antecedent position in the control conditions for either speed (free $t(16) = 1.6, p = .12$; fixed $t(16) = 1.0, p = .31$) or rate (free $t(16) = -0.1, p = .89$; fixed $t(16) = .4, p = .72$).

On average, the speed measure for local $ziji$ condition was 294ms faster (303ms for tied asymptote models) than long-distance $ziji$ condition (free asymptote models 95% CI: 52ms – 538ms; fixed asymptote models 95% CI: 79ms – 527ms).

**Discussion**

Both individual and average data suggest a time-course advantage for local $ziji$ conditions compared to LD $ziji$ conditions. In competitive model fits to the average time course data, there was a slight advantage for models that allocated different rate parameters to long-distance and local $ziji$ conditions; no such difference was observed for control comparisons. An analysis of the parameter estimates for individual participants showed that for the critical $ziji$ comparison, the local condition was processed significantly faster than the long-distance condition, as reflected in the rate parameter ($\beta$) and the composite speed measure ($\beta^{-1} + \delta$). No difference was observed in control conditions. In ANOVA analyses of empirical $d'$ scores, there was no significant difference for either $ziji$ or control comparisons in asymptotic accuracy.

**Follow-up experiment**
One unexpected finding in Experiment 1 was the high acceptance rate of the no antecedent *ziji* condition, which participants accepted on 47% of trials. It has been claimed that in the absence of an overt, syntactically prominent antecedent, *ziji* can refer to the speaker (Huang & Liu, 2001). However, post-experiment debriefing suggested that some speakers also interpreted *ziji* as coreferential with an implicit author of the inanimate main clause subjects such as *book* or *speech*. It is also possible that the subject contained in the temporal adjunct in our experimental sentences contributed to retrieval interference, and was misinterpreted as an antecedent for *ziji* on some trials. We conducted a follow-up experiment to determine the interpretations that comprehenders might assign to each of our three conditions.

The follow-up experiment used conditions 1-3 from Experiment 1. Twenty-four of the original 40 item sets were selected, and were distributed in a Latin Square fashion into three experimental lists. Each list was presented as a short questionnaire on the online experimental platform IbexFarm (Drummond, 2011). Each sentence was presented on the screen, and participants were instructed to choose their preferred interpretation of *ziji*’s antecedent from five options: the main clause subject, the local subject, the interfering subject contained inside the temporal adjunct, the speaker of the sentence, or none. When the main clause subject was inanimate (e.g. *book*), the main clause subject response option referred to the implicit author (e.g. *the book’s author*).

Seventeen native Mandarin speakers were recruited via the Internet. The results are presented in Table 4. In order to test for differences across conditions in the proportion of responses, each response category was converted into a binary variable that was 1 if a response was in the category, and 0 otherwise. Each response category was analyzed using logistic mixed effects models with crossed random intercepts for subjects and items and random slopes of condition for subjects. Two Helmert contrasts were employed for the condition factor: a locality contrast that compared local and LD conditions, and an antecedent contrast that contrasted the no antecedent condition with the average of the LD and local conditions.

This analysis revealed that the no antecedent condition had significantly more none responses ($\beta = .64$, Wald’s $z = 3.4$, $p < .001$) and interferer responses ($\beta = 1.53$, Wald’s $z = 6.1$, $p < .001$) than the other two conditions. The LD condition had significantly more matrix subject responses than the local conditions ($\beta = -3.5$, Wald’s $z = -8.0$, $p < .001$), and the local condition had significantly more embedded subject responses than the LD condition ($\beta = 3.4$, Wald’s $z = 8.8$, $p < .001$). In addition, there was a significant effect of antecedent on embedded subject responses ($\beta = -.9$, Wald’s $z = -5.2$, $p < .001$), reflecting the low proportion of local subject responses in the no antecedent condition. No other effects were significant.

The follow-up experiment confirms that participants overwhelmingly select a structurally prominent, animate antecedent for *ziji* when there is one available. This
replicates the judgments reported in the literature on Mandarin long-distance reflexives. Additionally, the results show that in the absence of a structurally prominent antecedent, comprehenders nonetheless ultimately prefer a sentence-internal antecedent: the interfering subject is selected on 31% of trials, and on 35% of trials participants coerce an animate antecedent from the matrix subject.

Discussion

The results of Experiment 2 confirm that comprehenders prefer to select syntactically prominent, animate antecedents for ziji in our materials. The results of Experiment 1 show that comprehenders are measurably slower to access long-distance antecedents for ziji than local antecedents. The fact that dependency distance impacted retrieval speed in our SAT experiment contrasts with previous SAT findings. Previous work on SAT in language comprehension suggests that distance does not affect the dynamics parameters in the SAT function (Foraker & McElree, 2007; Martin & McElree, 2008, 2009; McElree, 2000; McElree et al., 2003). This makes it unlikely that the faster access times we observe to local antecedents reflect a simple effect of temporal distance or recency.

Another way that long-distance and local antecedent configurations differ is in the type of interference contributed by the semantically inappropriate antecedent. In long-distance conditions, the semantically inappropriate antecedent intervenes between the target antecedent and the anaphor, and so generates retroactive interference (RI) in the retrieval process. Conversely, in local antecedent configurations, the long-distance antecedent precedes the target and anaphor, and so may generate proactive interference (PI) effects on the local target. Ötzekin and McElree (2007) observed that the presence of proactive interference has the effect of slowing down retrieval dynamics, possibility by preventing participants from using rapid assessments of familiarity in the recognition process. More recent SAT work has directly investigated the effects of PI and RI on retrieval processes in language comprehension (Van Dyke & McElree, 2011). Van Dyke and McElree (2011) suggest that RI contributes more difficulty in dependency completion in sentence comprehension than does PI, but crucially, they show that the type of interference (PI/RI) does not impact retrieval speeds in multiple-response SAT. Instead, they observe only that RI configurations lower asymptotic accuracy relative to PI configurations. In light of these results, it appears unlikely that the speed differences that we observed were due to the type of interference generated by the inappropriate antecedent.

A model of the local search hypothesis
We have suggested that neither recency alone nor the type of interference (RI/PI) was the source of the observed differences in retrieval times in Experiment 1. Instead, we argue that these results suggest that comprehenders consider or misretrieve the local subject position when the target antecedent is syntactically distant, which then leads to slowed retrieval of long-distance antecedents. We propose that this arises because locality outweighs semantic cues when retrieving an antecedent for ziji. There are two potential explanations of this locality effect in our data. According to the Local Search hypothesis, this effect reflects the use of cues that restrict retrieval operations to a local syntactic domain. However, it is possible that this locality effect reflects more misretrievals of a semantically inappropriate local subject simply because it has a relatively high resting activation. There are two reasons to suspect that the local subject might have higher resting activation prior to reaching the anaphor ziji. First, it is more recent, and so will have undergone less temporal decay. Second, the embedded subject forms a dependency with the verb that precedes ziji. The process of retrieving the subject to form this dependency may boost the embedded subject’s resting activation prior to encountering the anaphor.

To distinguish between a Local Search account and an account that attributes the slowed processing of LD ziji to the heightened activation of the local subject, we formalize the predictions of both accounts with a simple mathematical model of the antecedent retrieval process for ziji. Our model incorporates the declarative memory component of the ACT-R framework (Anderson & Lebiere, 1998), which implements a direct access cue-based retrieval process that is subject to temporal decay and retrieval interference. An attractive feature of this model is that it has been used in a number of successful models of cue-based parsers (Lewis & Vasishth, 2005; Lewis et al., 2006; Vasishth et al., 2008). Our goal in modeling the antecedent retrieval process using ACT-R is to estimate the effect of a local search strategy on SAT retrieval dynamics above and beyond the effects of interference and decay.

We define our retrieval models in terms of the set of cues (the retrieval probe) used to retrieve an antecedent from memory. The unrestricted retrieval model limits the probe to item information only. In our implementation, this includes category identity (NP), a case feature (+Nomative), which serves to identify subjects, and an animacy feature (+Animate). The latter two cues implement the syntactic and semantic constraints on ziji’s antecedent. The local search retrieval model includes these features plus a feature (+Local) that distinguishes the local clause from other clauses. In terms of our stimuli, this feature is used to distinguish the embedded clause from both the matrix clause and the adjunct clause. This feature implements the core claim of the Local Search hypothesis: that the parser uses positional information to restrict search to the local syntactic domain at retrieval, creating a retrieval process that explicitly prioritizes retrieval within a local syntactic domain (here taken to be the local clause).
Our model assumes that the process of finding ziji’s antecedent involves a series of serially executed, cue-based retrievals from a content-addressable memory store (consistent with the processing assumptions of Lewis & Vasishth, 2005). Once an item is retrieved, it is evaluated as the antecedent of ziji. If the retrieved item is rejected as an antecedent for ziji, then the processor samples another potential antecedent from the linguistic context, without replacement. We assume that the processor samples antecedents in this way until an appropriate antecedent is found. Under this model, cue match, temporal decay, and interference all influence the average number of sampling operations that are required to recover the correct antecedent for ziji. The more sampling operations are executed during the retrieval of an antecedent, the slower the speed of the SAT function that tracks this process.

To fit this model to the empirical data, we first determine the probability of successfully retrieving the target antecedent on each successive sampling operation. We determine these probabilities by simulation, using the equations that define declarative memory in ACT-R. Under this model, the parser retrieves the item in memory with the highest activation value, where activation is a function of the match to retrieval cues and the resting activation of all items in memory. Formally, the activation of a memory item $i$ ($A_i$) is the sum of its resting activation $B_i$, the match between the item and each of the $J$ retrieval cues in the probe ($S_j$), and random noise ($\epsilon$):

$$A_i = B_i + \sum_j W_j S_{ji} + \epsilon$$

(8)

The weight associated with each retrieval cue $W_j$ is the total amount of goal activation available $G$ divided by the number of retrieval cues. The resting activation of item $i$ is a function of temporal decay (controlled by the decay parameter $d$) over all $M$ intervals $t_m$ since the item was last retrieved or created:

$$B_i = \ln(\sum_m t_m^{-d})$$

(9)

The match of an item $i$ to the retrieval probe is the sum of a weighted associative boost for each cue $S_j$ in the retrieval probe that matches the features of item $i$. The weight of a feature $W_j$ is assumed to be equal across all cues in the probe. The associative boost that a given cue adds to an item it matches is reduced by the fan of that cue, or the number of items in memory that match that cue:

$$S_{ji} = S - \ln(fan_j)$$

(10)

Lastly, a small amount of stochastic noise is added to every item’s activation level. On any given trial a noise value is drawn from a logistic distribution with a mean of zero and a variance that is controlled by a noise parameter $s$. 

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For all predictions reported below, we simulated the model’s predictions on a range of parameter settings, and report the mean predicted values across all parameter settings (following the approach in Dillon et al., 2013). Our choices of possible parameter settings were based on the settings reported in Lewis and Vasishth (2005). One exception was the scaling parameter $F$, which was set to yield a mean retrieval time of 90ms. This was chosen because it provided a close fit to the estimated retrieval time of 85ms in the SAT paradigm found by McElree and colleagues (2003). The intervals between item creation and the retrieval associated with $ziji$ were calculated directly from the experimental presentation parameters. In addition, an intermediate retrieval of the local subject at the embedded verb was simulated, which provided a boost in the embedded subject’s resting activation prior to the point when $ziji$ was encountered.

For both retrieval models, the probability of retrieving the target and each of the distractor NPs under these conditions was estimated using Monte Carlo simulation and averaging across all parameter settings considered. From this distribution we simulated the average number of sampling operations necessary to recover the target antecedent for both retrieval models. The resulting distributions are presented in Table 5. Under local search models, the local target is reliably retrieved after only one sampling operation on 56% of trials, whereas the modal number of sampling operations required to access the long-distance antecedent under the search model is 3 (occurring on 55% of trials). In the unrestricted search models, there is a lower probability of success with a single retrieval: local antecedents are retrieved on the first trial in 35% of trials for unrestricted models, and long distance antecedents are retrieved on 27% of trials. The lower probability of success for unrestricted models reflects the additional interference from the syntactically illicit distractor NP that occurs without positional cues to retrieval. On unrestricted models the number of sampling operations necessary to recover the target antecedent does not appear to differ substantially for local and long-distance antecedents. This pattern suggests that the increased resting activation of the local subject does not by itself lead to a substantially increased rate of retrieval errors during the retrieval of a long-distance antecedent. Instead, the search model results suggest that a semantically inappropriate local subject is most likely to be misretrieved when the search probe contains positional cues that select the local subject.

$\epsilon \sim \text{logistic}(0, \sigma^2)$

$\sigma^2 = \frac{\pi^2}{3} S^2$

1 The parameter settings considered were: $F = \{0.08, 0.10, 0.12\}; d = \{0.4, 0.5, 0.6\}, S = \{0.75, 1.0, 1.25\}; G = \{0.75, 1.0, 1.25\}$. Crossing all possible parameter settings resulted in 81 unique models.
Next, we calculated the distribution of finishing times for the search process under the serial sampling model we have proposed. We simulated the distribution of finishing times for a retrieval process with $n$ sampling iterations by simulating the sum of $n$ retrievals from the ACT-R model given above. For retrievals beyond the first, an additional 50ms was added, reflecting the additional processing necessary to evaluate the retrieved item. In ACT-R, the retrieval latency $T_i$ is a function of activation and a scaling parameter $F$ (see footnote 1):

$$T_i = Fe^{-A_i}$$

Inspection of the resulting finishing time distributions showed that they were well fit by gamma distributions. Therefore we modeled the overall predicted finishing time distribution for a given retrieval model as a mixture of gamma distributions, with each component reflecting the distribution of finishing times for a process with $n$ sampling iterations. The mixing probabilities on each component were provided by the distribution in Table 5. With this mixture distribution, we could then follow the modeling approach advanced by McElree (1993). To do this, we used the resulting mixture to model the probability that the retrieval process will have completed by any time $t$ as the cumulative distribution of this mixture, offset by a constant base encoding time $\delta$ (McElree, 1993):

$$P(T \leq t) = \frac{\beta^\alpha}{(\alpha-1)!} \int_0^{t-\delta} e^{-\beta t'} t'^{\alpha-1} dt'$$

$t > \delta$, else 0.

This cumulative distribution was then used to estimate the probability of responding with a hit at each time point $t$. This was calculated following the method described in McElree (1993). In particular, we assumed that all unfinished processes at time $t$ contributed a hit 50% of the time, reflecting a guess on the part of the participant. We additionally assumed that on 5% of trials the target antecedent was rejected, leading to a miss response. The predicted proportion of hits at each time point was then transformed using the inverse cumulative normal distribution. Finally, the SAT function was fit to the predicted curves for each retrieval model and parameter setting, and the speed measure $\beta^{-1} + \delta$ was estimated for each predicted curve. We define the \textit{locality advantage} as the predicted speed to access a long-distance antecedent minus the predicted speed to access a local antecedent, given a set of model parameters and a retrieval probe. The predicted locality advantages were calculated for both retrieval models, under all parameter settings. The predicted locality advantages were then compared to the empirical locality advantage in speed observed in Experiment 1.

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1 50ms is the time necessary to execute a single production step in ACT-R.
Figure 3 provides a comparison of the empirical locality advantage with the predicted locality advantages for unrestricted and local search models. It can be seen that the local search model provides a good fit to the SAT data. On average, local search models predicted a locality advantage of 143ms, approximately half of the observed empirical estimate of 294ms from Experiment 1. However, the unrestricted search model predicts a much smaller speed advantage for local antecedents (39ms). We tested the fit of each candidate retrieval model to the data by comparing the distribution of predicted locality advantage effects to the distribution of the mean locality effect estimated in Experiment 1. From these distributions, we calculated Bayes factors using the model comparison approach advocated by Gallistel (2009). This comparison gives 5:1 odds in favor of the local search model over the unrestricted model, providing ‘substantial’ evidence in favor of the Local Search model (Jeffreys, 1961).

The modeling results suggest that the local search model provides a better explanation of our experimental data than does an account in which the locality advantage is simply attributed to the activation of the local subject. We note that the model does confirm that an unrestricted model of antecedent retrieval can predict a small speed difference, due to the interaction of temporal decay, retroactive interference, and reactivation of the local subject prior to the anaphor. However, given the modeling assumptions here, these factors alone were not sufficient to allow the model to capture the findings of Experiment 1. By providing evidence against these plausible alternative explanations for the results of Experiment 1, the findings from the computational simulations lend additional support to the Local Search hypothesis.

Discussion

Summary of results

The current study presented time-course data from the MR-SAT paradigm on the processing of the Mandarin Chinese long-distance reflexive ziji. Non-linear regressions using the SAT function revealed that the parameters that describe the speed of processing (specifically, rate and speed) were significantly faster for sentences containing a local antecedent for ziji than for sentences with a long-distance antecedent for ziji. Control conditions without any anaphoric dependency showed no difference in speed or rate parameters. There were no significant differences in accuracy for either control or ziji conditions. A follow up experiment evaluated the interpretations that comprehenders assigned to ziji to a subset of our experimental materials. These results confirmed that participants overwhelmingly interpreted a local animate subject as the preferred antecedent for ziji when it was present, and likewise when there was a long-distance animate subject present. However, when there was no syntactically licit animate subject in the sentence, participants either rejected ziji as antecedentless, interpreted ziji as
coreferent with an implicit possessor argument in the highest subject position, or interpreted it as coreferent with an animate subject embedded inside a temporal adjunct clause.

To aid in interpreting these data, we fit the predictions of two retrieval models to the SAT data. The Local Search model implemented a retrieval process that used positional syntactic cues to restrict retrieval to the local clause. The Unrestricted model used only item information to access potential antecedents. We showed that the Local Search model provided a closer fit to the empirical data than the Unrestricted model, using plausible parameter estimates.

**Locality in retrieval**

The slower time course to access the matrix subject suggests that comprehenders initially access the local subject position when retrieving an antecedent for *ziji*, even if that position does not contain a grammatically licensed antecedent. The results of our simulations suggest that this misretrieval of the local subject is not merely due to a higher resting activation for local subject positions compared to more distant subject positions. Instead, the models suggest that comprehenders attempt to use retrieval cues to limit search to the local syntactic domain. This supports the key claims of the Local Search hypothesis: comprehenders attempt to limit retrieval to the local clause, even for dependencies that are not strictly clause-bounded. This suggests that in at least some cases, locality effects in processing do not simply reflect decay and interference processes. In some cases, they additionally reflect a search strategy that favors the retrieval of syntactically local dependents.

One interesting finding from Experiment 1 is the individual variation in the retrieval dynamics observed across participants. Four of the seventeen participants showed substantially faster retrieval of the long-distance antecedent than the local antecedent. For these participants, the average speed advantage seen for long-distance antecedents was 343ms. This variation raises the possibility that the positional cues used to retrieve an antecedent are under strategic control, such that these four participants were able to prioritize retrieval of the highest subject over the local subject. Additionally, two of the remaining thirteen participants showed a substantial rate advantage for the local conditions, driven by extremely fast retrieval speeds for local *ziji* conditions. The extremely rapid growth of these participants’ SAT functions suggests that they may have adopted a distinct strategy for determining whether *ziji* was licensed in our experiment, perhaps one based on familiarity with an animate referent rather than full retrieval of an antecedent. Although we believe it is important to understand the variation observed across our participants, we caution that these suggestions are for the moment highly speculative. Further research is necessary to determine the exact ways in which memory search strategies are subject to strategic and individual variation.
The present results are consistent with existing evidence that shows an online locality bias when processing *ziji*. For example, Li and Zhou (2010) provide ERP evidence that long-distance binding of *ziji* elicits a larger P300/600 response relative to local or ambiguous binding of *ziji*, suggesting greater processing difficulty associated with recovering long-distance interpretations. In addition, cross-modal priming studies have shown that local antecedents are more quickly reactivated than long-distance antecedents upon encountering *ziji* (Gao, Liu & Huang, 2005; Liu, 2009). Chen, Jäger and Vasishth (2012) also present self-paced reading evidence that comprehenders process local *ziji*-antecedent dependencies more quickly than long-distance dependencies. The present study goes beyond these studies by providing evidence that the processing advantage for local *ziji* dependencies reflects an advantage in processing speed, not (just) processing accuracy.

We presented a model of the Local Search strategy that relies on a direct access memory architecture. On this model, the slowdown for retrieving the matrix antecedent reflects the fact that comprehenders must execute multiple retrieval operations to recover the distant antecedent in the face of a substantive locality bias in retrieval. However, the data are also compatible with a serial scan mechanism that operates over syntactic structures. This is compatible with previous claims about the mechanisms that allow the recovery of order or positional information in retrieval (Gronlund, Edwards & Ohrt, 1997; McElree & Dosher, 1993). On this model, the present results do not reflect misretrieval of the local subject, but rather a backwards process of traversing the parse until a grammatically licensed antecedent is encountered. Although existing SAT data provide evidence against the use of serial search processes for a number of linguistic dependencies, it is possible that a serial search process is applied uniquely to syntactic binding dependencies. Indeed, such a serial, backwards search process for the retrieval of a reflexive anaphor’s antecedent has been argued for on computational grounds by Berwick and Weinberg (1984). However, our present results do not distinguish between these two distinct mechanisms.

Although we have argued that our simulations point to a role for a Local Search strategy in memory access, it is true that this argument rests on a number of modeling assumptions that we made. It is possible that the SAT results reflect an overwhelming activation advantage for the local subject that is not captured in our implemented retrieval model, which might lead to slowed access to the distant subject even without the use of positional cues. One way this might occur is if the local subject were available in the focus of attention at the point of processing the anaphor, thus obviating the need for any retrieval process (Jonides, Lewis, Nee, Lustig, Berman & Moore, 2008; McElree, 2006). This interpretation seems less likely in light of findings that indicate that the focus of attention is extremely limited in size and scope, possibly corresponding to just one task-relevant encoding (McElree, 1998; McElree & Dosher, 1989). If only one element occupies focal attention before *ziji* is processed, it is likely to be the verb, although it is
difficult to generalize from findings about the scope of attention in recognition memory tasks to sentence processing. The data on the capacity of the focus of attention is somewhat sparser for connected linguistic representations, which have considerably richer structure than lists. However, it has been shown that opening a new clause displaces the contents of focal attention (McElree et al., 2003; Wagers & McElree, 2009), and so the adverbial clause that intervened between the subject and the verb in Experiment 1 is likely to have displaced the local subject from active memory.

A second possibility is that the local subject is reactivated at the verb that precedes ziji. Although our model accounted for a process of local subject reactivation prior to the anaphor, it is possible that the boost given to the local subject due to this reactivation is substantially larger than our model allows for. At present we cannot rule out this possibility, but we believe that it is unlikely on empirical grounds. In particular, data from the cross-modal lexical priming paradigm show that a subject is not strongly activated above baseline while processing its verb (Nicol & Swinney, 1989; Nicol & Swinney, 2003). Studies that have contrasted activation of the local subject position before and after reflexive anaphors demonstrate that reactivation of the local subject is contingent on the construction of an anaphoric dependency; processing the verb alone is not sufficient to boost activation, nor is activation observed in post-verbal positions that do not contain a reflexive anaphor (see a review in Nicol & Swinney, 2003).

**Interpretations of ziji**

One surprising finding from Experiment 1 is that sentences that do not contain an explicit linguistic antecedent for ziji were accepted by our participants on 47% of trials. Descriptions of the licensing conditions on ziji suggest that in sentences with no intrasentential antecedent, it is possible to construe ziji as referring the speaker of the sentence. This pragmatic, egocentric interpretation is thought to be due to the prominent discourse status of the speaker (Huang & Liu, 2001; Kuno, 1972). Contrary to these reports, however, we observed in the follow-up experiment that participants almost never recovered the egocentric interpretation with our experimental materials. Instead, there was an overwhelming preference to construe ziji with an intrasentential antecedent. In the LD and Local conditions, when there was a syntactically prominent animate antecedent available in the sentence

For no antecedent sentences, the most common response was that ziji referred to an implicit author associated with the inanimate matrix subject. It has been reported that if the head of a noun phrase is inanimate, ziji may refer to an animate possessor argument in that noun phrase in a ‘subcommand’ configuration (Huang, Li & Li, 2009). It is possible then that participants recovered a syntactic antecedent in a subcommanding configuration in the context of our experiment, albeit with a null pronominal element that is taken to refer to the implicit author. To our knowledge this interpretation has not been
reported previously for *ziji*, and further work is necessary to determine the constraints that govern this interpretation.

Additionally, many participants in the follow-up experiment indicated that *ziji* could corefer with the syntactically illicit distractor in the *no antecedent* configurations. Similar findings have been reported for offline questionnaire studies of English reflexives (Sturt, 2003). It is possible that grammatically illicit interpretations of this sort arise due to retrieval interference (Chen, Jäger & Vasishth, 2012), but we note that it is difficult to draw a direct link between the responses in the offline questionnaire and online parsing processes. Furthermore, responses to this condition must be treated with caution: if for some participants, the ‘no antecedent’ sentences were truly ungrammatical, then it is not clear on what basis participants chose one interpretation of *ziji* over another.

**Conclusion**

The present study examined the time-course of antecedent retrieval for the Mandarin Chinese long-distance anaphor *ziji*. It was found that *ziji* is processed more quickly with a local antecedent than with a long-distance antecedent. A computational model of the retrieval process supports the conclusion that the locality advantage observed when retrieving *ziji*’s antecedent reflects an explicit local search strategy: when retrieving an antecedent, comprehenders prioritize retrieval of items within the local clause. These results suggest that locality effects in sentence processing cannot be entirely reduced to the effects of temporal decay and interference in memory.

**Acknowledgments**

This work was supported in part by NSF EAPSI-091387 to BD, by NSF IGERT DGE-0801465 to the University of Maryland, by NSF BCS-0848554 to CP, and by a Natural Science Foundation of China grant (31170970) to TG. We would like to thank Brian McElree for his extensive advice on the current work, as well as Rick Lewis for his help in performing the ACT-R simulations reported here. We are also grateful to the members of the Department of Linguistics at the University of Maryland, Stephani Foraker, Lyn Frazier, Roger Levy, Julie Van Dyke, Shravan Vasishth and Ming Xiang for useful discussions of the material presented here, and to Mehmeti Abdullah, Julianne Chaloux, Peiyao Chen, Yangsook Park, and Yu Kai for assistance in collecting data and preparing experimental materials.
References


Drummond, A. (2011) *IbexFarm (Version 0.2.7) [Software].* Available from http://spellout.net/ibexfarm/


<table>
<thead>
<tr>
<th>#</th>
<th>Condition</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LD antecedent</td>
<td>张教练 表明 那篇报导 [在 团队 未能 发挥 水准 的时候] 低估了 自己 Coach Zhang say [that report [when team not perform well time] underestimate self when the team was doing poorly.]</td>
</tr>
<tr>
<td>2</td>
<td>Local antecedent</td>
<td>回忆录 表明 张教练 [在 团队 未能 发挥 水准 的时候] 低估了 自己 Auto-biography say [coach Zhang [when team not perform well time] underestimate self] when the team was doing poorly.]</td>
</tr>
<tr>
<td>3</td>
<td>No antecedent</td>
<td>*回忆录 表明 那篇报导 [在 团队 未能 发挥 水准 的时候] 低估了 自己 *Auto-biography say [that report [when team not perform well time] underestimate self] when the team was doing poorly.]</td>
</tr>
<tr>
<td>4</td>
<td>LD control</td>
<td>张教练 表明 那篇报导 [在 团队 未能 发挥 水准 的时候] 低估了 那位击球手 Coach Zhang say [that report [when team not perform well time] underestimate that batsman] when the team was doing poorly.]</td>
</tr>
<tr>
<td>5</td>
<td>Local control</td>
<td>回忆录 表明 张教练 [在 团队 未能 发挥 水准 的时候] 低估了 那位击球手 Auto-biography say [coach Zhang [when team not perform well time] underestimate that batsman] when the team was doing poorly.]</td>
</tr>
<tr>
<td>6</td>
<td>No antecedent control</td>
<td>回忆录 表明 那篇报导 [在 团队 未能 发挥 水准 的时候] 低估了 那位击球手 Auto-biography say [that report [when team not perform well time] underestimate that batsman] when the team was doing poorly.]</td>
</tr>
<tr>
<td>7</td>
<td>LD control anomaly</td>
<td>*张教练 表明 那篇报导 [在 团队 未能 发挥 水准 的时候] 低估了 眼镜 *Coach Zhang say [that report [when team not perform well time] underestimate the glasses] when the team was doing poorly.]</td>
</tr>
<tr>
<td>8</td>
<td>Local control anomaly</td>
<td>*回忆录 表明 张教练 [在 团队 未能 发挥 水准 的时候] 低估了 眼镜 *Auto-biography say [coach Zhang [when team not perform well time] underestimate the glasses] when the team was doing poorly.]</td>
</tr>
<tr>
<td>9</td>
<td>No antecedent control anomaly</td>
<td>*回忆录 表明 那篇报导 [在 团队 未能 发挥 水准 的时候] 低估了 眼镜 *Auto-biography say [that report [when team not perform well time] underestimate the glasses] when the team was doing poorly.]</td>
</tr>
</tbody>
</table>

**Table 1:** Summary of conditions in experiment: Critical *ziji* conditions. Critical conditions are 1-2 and 4-5; conditions 3 and 6-9 were included for purposes of *d’* scaling (see text).
<table>
<thead>
<tr>
<th></th>
<th><em>ziji</em></th>
<th>Control</th>
</tr>
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<tbody>
<tr>
<td>Long-distance Animate</td>
<td>1.26 (± .12)</td>
<td>1.53 (± .12)</td>
</tr>
<tr>
<td>Local Animate</td>
<td>1.11 (± .13)</td>
<td>1.33 (± .13)</td>
</tr>
</tbody>
</table>

**Table 2:** Mean empirical pseudo $d'$ values, obtained by averaging accuracies over final four response latencies. By-participant standard error in parentheses.
Table 3: By-subject and average parameter estimates for critical ziji comparisons, along with average parameter estimates for control comparisons.

<table>
<thead>
<tr>
<th></th>
<th>LD R^2</th>
<th>Loc R^2</th>
<th>Asymptote (λ, d')</th>
<th>Rate (β, s^{-1})</th>
<th>Intercept (δ, s)</th>
<th>Speed (β^{-1}+δ, s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Asymptote LD</td>
<td>Rate LD</td>
<td>Intercept LD</td>
<td>Speed LD</td>
</tr>
<tr>
<td>Average</td>
<td>0.99</td>
<td>0.98</td>
<td>1.30 1.15</td>
<td>0.95 1.27</td>
<td>0.72 0.74</td>
<td>1.76 1.53</td>
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<tr>
<td>S1</td>
<td>0.98</td>
<td>0.96</td>
<td>0.95 0.72</td>
<td>3.51 15.00</td>
<td>0.29 0.30</td>
<td>0.58 0.37</td>
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<tr>
<td>S2</td>
<td>0.75</td>
<td>0.94</td>
<td>1.66 1.55</td>
<td>2.81 3.90</td>
<td>0.93 0.89</td>
<td>1.29 1.15</td>
</tr>
<tr>
<td>S3</td>
<td>0.97</td>
<td>0.98</td>
<td>2.00 0.95</td>
<td>0.72 1.38</td>
<td>0.88 0.96</td>
<td>2.27 1.69</td>
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<tr>
<td>S4</td>
<td>0.99</td>
<td>0.86</td>
<td>0.95 1.75</td>
<td>3.87 1.95</td>
<td>0.65 0.68</td>
<td>0.90 1.20</td>
</tr>
<tr>
<td>S5</td>
<td>1.00</td>
<td>0.98</td>
<td>0.68 0.30</td>
<td>0.86 15.00</td>
<td>0.28 0.54</td>
<td>1.44 0.61</td>
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<tr>
<td>S6</td>
<td>0.99</td>
<td>0.98</td>
<td>0.93 0.59</td>
<td>1.36 3.57</td>
<td>1.08 1.25</td>
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<tr>
<td>S7</td>
<td>0.95</td>
<td>0.96</td>
<td>1.89 2.21</td>
<td>2.08 1.77</td>
<td>0.57 0.58</td>
<td>1.05 1.15</td>
</tr>
<tr>
<td>S8</td>
<td>1.00</td>
<td>0.93</td>
<td>1.05 2.26</td>
<td>3.81 0.97</td>
<td>1.58 1.26</td>
<td>1.84 2.29</td>
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<tr>
<td>S9</td>
<td>0.91</td>
<td>0.96</td>
<td>1.76 0.44</td>
<td>1.09 4.65</td>
<td>1.66 1.92</td>
<td>2.58 2.14</td>
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<tr>
<td>S10</td>
<td>0.97</td>
<td>0.97</td>
<td>0.57 0.99</td>
<td>1.67 3.27</td>
<td>1.18 1.44</td>
<td>1.78 1.75</td>
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<tr>
<td>S11</td>
<td>0.98</td>
<td>0.99</td>
<td>1.65 0.97</td>
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<tr>
<td>S12</td>
<td>0.94</td>
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<td>S13</td>
<td>1.00</td>
<td>0.99</td>
<td>0.40 0.76</td>
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<td>S15</td>
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<td>0.92</td>
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<tr>
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<td>0.99</td>
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<td>1.71 1.64</td>
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<tr>
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<td>2.03 1.67</td>
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<td>0.97 0.91</td>
<td>0.77 0.79</td>
<td>1.80 1.89</td>
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<tr>
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<td>Interfering</td>
<td>Speaker</td>
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<tr>
<td>------------------</td>
<td>---------------</td>
<td>-------</td>
<td>-------------</td>
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<tr>
<td>LD antecedent</td>
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<td>0.06</td>
<td>0.03</td>
<td>0.00</td>
<td>0.04</td>
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<tr>
<td>Local antecedent</td>
<td>0.03</td>
<td>0.91</td>
<td>0.03</td>
<td>0.00</td>
<td>0.03</td>
<td></td>
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<tr>
<td>No antecedent</td>
<td>0.35</td>
<td>0.12</td>
<td>0.31</td>
<td>0.04</td>
<td>0.18</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4**: Average proportion of interpretations reported on critical *ziji* comparisons in the follow-up experiment.
<table>
<thead>
<tr>
<th>P(number of samples = X)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD Antecedent, Unrestricted</td>
<td>0.270</td>
<td>0.385</td>
<td>0.345</td>
</tr>
<tr>
<td>Local Antecedent, Unrestricted</td>
<td>0.353</td>
<td>0.437</td>
<td>0.210</td>
</tr>
<tr>
<td>LD Antecedent, Local Search</td>
<td>0.190</td>
<td>0.258</td>
<td>0.552</td>
</tr>
<tr>
<td>Local Antecedent, Local Search</td>
<td>0.560</td>
<td>0.351</td>
<td>0.089</td>
</tr>
</tbody>
</table>

**Table 5:** Probability distribution over the average number of sampling operations necessary to recover ziji’s antecedent for the critical experimental conditions, for each of the candidate retrieval models.
**Figure 1:** Example of a hypothetical SAT function describing growth in accuracy (in $d'$ units) accuracy over time. The SAT function reflects i) a period of chance performance, characterized by the intercept parameter, ii) a period of monotonic growth, whose slope is described by the rate parameter and iii) a period of terminal accuracy, indexed by the asymptote parameter.
Figure 2: Time course data (points) and best-fit SAT functions (lines) to average pseudo $d'$ scores in Experiment 1, for *ziji* and control conditions.
**Figure 3**: Comparison of empirical speed advantage for local *ziji* antecedents and search model’s predictions, given both unrestricted and local search retrieval probes. For model predictions, error bars represent 95% confidence interval of predicted locality advantage over parameter settings. For empirical data, error bars represent 95% confidence interval of true speed advantage for local antecedents by participants.