**The cue-based retrieval theory of sentence comprehension:
New findings and new challenges**

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Abstract

An active question in psycholinguistics concerns how speakers mentally encode and retrieve linguistic representations in memory during sentence comprehension. In this paper, we briefly review contemporary perspectives on memory retrieval in sentence comprehension, focusing on accounts of dependency resolution, and present new puzzles and challenges for existing models. We propose that the current data support the conclusion that linguistic dependencies are resolved using a direct-access, cue-based retrieval mechanism that gives preferential weighting to syntactic information when navigating linguistic representations in memory. We then discuss current empirical and theoretical gaps, highlighting areas in need of further research.

1. Introduction

A defining property of natural language is the ability to establish linguistic relations between non-adjacent pieces of information, creating 'long-distance' dependencies. A parade case involves the relationship between a verb and its subject, which can be separated by multiple words, phrases, or clauses, as in (1a). Other examples include anaphora and ellipsis, where the interpretation of expressions like *themselves* (1b) or *did too* (1c) depends on previously interpreted material.

(1) a. <u>The astronomer</u> who discovered the new planet proudly <u>revealed</u> the big findings.
    b. <u>The students in the class</u> doubted <u>themselves</u> during the exam.
    c. The professor <u>read the book</u> and the students <u>did too</u>.

Each of these dependencies is subject to different syntactic, semantic, and discourse constraints, which must be calculated incrementally as the sentence unfolds. The literature has

offered two competing accounts of the memory system that supports these calculations (see Van Dyke, Johns, & Kukona, 2014 for a review). Capacity accounts (Just & Carpenter, 1992; Gibson, 2000) assume that successful interpretation depends on the memory capacity of the individual—if a comprehender can adequately maintain dependent constituents, then comprehension will succeed. An alternative view (Lewis, Vasishth, & Van Dyke, 2006; McElree, Foraker, & Dyer, 2003) suggests that the amount of memory required for incremental parsing is extremely limited, making the size of an individual's memory capacity inconsequential for interpretation. Rather, comprehension is determined by how well an individual can *retrieve* necessary constituents. A number of retrieval mechanisms are theoretically possible, including those that employ serial or parallel search, or those driven by an associative direct access mechanism.[1]

In this paper, we argue that existing findings on the timing and accuracy of dependency formation are best captured with a direct-access retrieval mechanism that gives preferential weighting to syntactic information when navigating linguistic representations in memory. We begin in Section 2 by summarizing the evidence for direct-access retrieval in sentence comprehension, as well as additional evidence for the primacy of syntactic cues. In Section 3, we summarize several challenges for the proposed framework and offer suggestions for how they might be addressed in order to build a broader theory of the role of memory retrieval in sentence processing. We conclude in Section 4.

2. Memory retrieval in sentence comprehension

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[1] It is important to distinguish direct access, which entails directly identifying constituents via their content (content-addressability), from parallel search, which involves a simultaneous match of a retrieval probe to all items in memory. Under some formulations of parallel search (e.g., Anderson, 1974; Murdock, 1971; Townsend & Ashby, 1983), efficiency can depend on either the number of concurrent comparisons, or the strength of items in memory. The present discussion takes direct access to involve the simultaneous match of all items in memory, with efficiency depending solely on item familiarity (see McElree & Dosher, 1989; Dosher & McElree, 1992).

Direct access memory retrieval is characterized by a global matching process in which a composite retrieval probe, assembled from cues derived from the current context and grammatical knowledge, is matched against all previously encoded constituents in memory (Clark & Gronlund, 1996). The likelihood of retrieving a given item is determined by how closely that item matches the retrieval probe, taking into consideration the possibility that other items that also match the cues may be erroneously retrieved. This type of retrieval is described as *content-addressable*, since items are accessed based on their content, not their location (McElree, 1998, 2000, 2006; McElree & Dosher, 1989, 1993; McElree, Foraker, & Dyer, 2003; see also Kohonen, 1980). This mechanism stands in contrast to a serial *search* mechanism, in which the constituents of a sentence are examined individually, typically in sequence, until a match to the retrieval probe is found. This type of retrieval underlies the recovery of relational information (Gronlund, Edwards, & Ohrt, 1997; McElree, 2001, 2006; McElree & Dosher, 1993), and can proceed by scanning the syntactic representation of the sentence, node-by-node (Knuth, 1965), until the desired item is found. Serial search could be implemented as a separate retrieval mechanism or else by a hybrid system of scheduled or ranked direct-access retrievals (but see Gillund & Shiffrin, 1984 for evidence against hybrid systems).

Serial and direct-access operations have complementary advantages and disadvantages. With a direct-access mechanism, retrieval speed is unaffected by the amount of information to be searched through. Retrieval time is *fast* and *constant* with distance, because items are contacted associatively via their content. However, these advantages come with a tradeoff: incorrect items can interfere with retrieval of the target or can even be mis-retrieved if they sufficiently match the retrieval cues. A serial search mechanism, on the other hand, can avoid interference from similar distractors through a systematic evaluation of each intervening item, but search time will increase

with the number of items in the representation or the number of memory comparisons required to obtain the desired item. This property provides a crucial diagnostic: measures of retrieval speed can be used to identify which type of retrieval process is used in sentence comprehension.

Obtaining adequate data is hardly trivial, however, as most typical measures of retrieval time (e.g., reaction times or reading times) confound speed and accuracy in relation to participant-specific response criteria (e.g., Wickelgren, 1977; Schouten & Bekker, 1967; for sentence processing, see Forster 1979, Wotschack 2009, Lewis, Shvartsman & Singh 2013). While a number of experimental and statistical solutions to this problem exist (for recent discussion, cf. Davidson & Martin, 2013; Loeys, Rosseel, & Baten, 2011), the method that has had the most impact in sentence processing research has been the use of the response signal speed-accuracy tradeoff (SAT) task (e.g. Reed, 1973; Dosher, 1976; McElree & Dosher, 1993; Wickelgren et al., 1977). In this task, participants read sentences presented via rapid serial visual presentation (RSVP) and make binary judgments about sentence acceptability at cued intervals, ranging from before the critical dependent until 5-6 seconds after the dependent constituents will have been integrated. Participants' average performance at different cue times is interpolated into an exponential curve that summarizes the entire speed-accuracy tradeoff function, revealing the time course of retrieving the information necessary to correctly interpret the sentence. Importantly, by sampling a wide enough range of intervals, independent estimates of retrieval speed and response accuracy are available. These unconfounded parameters can be used to assess effects of amount of information in the search space on retrieval speed.

Evidence of constant time access. A number of findings suggest that retrieval times are unaffected by the length of the dependency, as expected in a direct-access system. For instance,

McElree and colleagues tested filler-gap dependencies, such as those in (2) using SAT measures, and found that interpolating varying amounts of linguistic material between the the filler, e.g., *the book*, and its gap position after the sentence-final verb negatively impacted asymptotic accuracy, but did not impact retrieval speed (McElree, 2000; McElree et al., 2003). Similar effects have been reported for subject-verb dependencies, as in (3), which varies the number of semantically suitable subject distractors (Van Dyke & McElree, 2011). McElree and colleagues presented these findings as evidence for a set-size invariant direct-access mechanism, where the cues at retrieval are used to directly identify the target dependent.

(2) a. This was the book that the editor admired.
   b. This was the book that the editor who the receptionist married admired.
   c. This was the book that the editor who the receptionist who quit married admired.

(3) a. The attorney who the judge realized had declared that the motion was appropriate compromised.
   b. The attorney who the judge realized had declared that the witness was appropriate compromised.

One crucial objection raised by Martin and McElree (2008) is that dependencies like those in (2 & 3) may not involve retrieval. Instead, they could be resolved using a predictive strategy that searches for a gap site in (2), or a down-stream verb in (3), in advance of bottom-up evidence ('active-gap filling'; Crain & Fodor, 1985; Fodor, 1978; Garnsey, Tanenhaus, & Chapman, 1989; Stowe, 1986; Traxler & Pickering, 1996). To address this issue, Martin and McElree tested antecedent-ellipsis dependencies, like those in (4), in which the upcoming ellipsis is unheralded, hence forestalling any predictive strategies (Martin & McElree, 2008, 2009, 2011). Although comprehenders were unable to anticipate the dependency, Martin and McElree consistently found that retrieval times remained constant, regardless of dependency length.

(4) a. The editor admired the author's writing, but the critics did not.
    b. The editor admired the author's writing, but everyone at the publishing house was shocked to hear that the critics did not.

These studies show that for a range of linguistic dependencies, retrieval is unaffected by the length of the dependency or the number of distractors, as expected in a direct-access, cue-based system, and that in at least some cases, this effect persists when prediction is not possible.

Evidence of interference. Another source of evidence for direct-access comes from profiles of retrieval errors. In a direct-access system, matching a set of retrieval cues against all items in parallel enables constant time retrieval, but also creates the opportunity for errors. Retrieval errors arise when the similarity of a distractor to the target or retrieval cues impedes access to the target. This effect, known as *similarity-based interference*, is well-documented in the verbal memory literature (see Van Dyke & Johns, 2010, for discussion.) Research on memory retrieval in sentence comprehension has identified two types of similarity-based interference that can arise during dependency formation: *inhibitory interference* and *facilitatory interference*.

Inhibitory and facilitatory interference effects occur in different contexts and have different behavioral signatures. Inhibitory interference occurs when access to the target is disrupted by other items in memory that overlap in feature content with the target, and manifests as increased difficulty during dependency formation. When multiple items overlap with the target, the target will become less distinct in memory, due to either memory overwriting (Nairne, 1988, 1990; Oberauer & Kliegl, 2006), or decreased distinctiveness of cues at retrieval ("cue overload"; Nairne, 2002; Öztekin & McElree, 2007; Watkins & Watkins, 1975). Both will interact to inhibit access to the target, and the severity of the effect will increase in proportion to the number of items that

overlap with the target (the "fan"; Anderson, 1974; Anderson & Reder, 1999). Facilitatory interference, by contrast, manifests as a speed-up in the presence of a distractor in cases where a perfect match is *not* available relative to when there is no distractor. Such effects have been argued to reflect incorrect retrieval of a distractor from content-addressable memory. Both inhibitory and facilitatory interference have been studied in the context of sentence processing.

For instance, Van Dyke and McElree (2006) examined how the degree of overlap between the features of the target and non-target items in memory impacts the processing of subject-verb dependencies. In a dual-task paradigm, participants were asked to memorize three nouns, e.g., *table—stove—truck*, and then read sentences like those in (5). The nouns in the memory list were either semantically compatible with the sentence-final verb (5b) or semantically incompatible (5a). Van Dyke and McElree observed longer reading times for verbs that were compatible with the nouns in the memory list as compared to verbs that were incompatible. These findings show that retrieval of the target is disrupted when other items in memory share some of its features (see also Fedorenko, Gibson, & Rhode, 2006; Van Dyke & Lewis, 2003). Van Dyke and McElree attributed these effects to cue-overload at retrieval, where the cues needed to retrieve the target become associated with different items in memory and can no longer reliably elicit the target.

(5) a. It was the boat that the guy who lived by the sea sailed.
    b. It was the boat that the guy who lived by the sea fixed.

A similar inhibitory effect of semantic distractors embedded within the sentence was observed by Van Dyke (2007), with increased sentence final reading times and reduced comprehension accuracy to (6b & d) as compared with (6a & c).

(6) a. The pilot remembered that the lady who was sitting in the smelly <u>seat</u> yesterday moaned.

b. The pilot remembered that the lady who was sitting near the smelly <u>man</u> yesterday moaned.
c. The pilot remembered that the lady who said that the seat was smelly yesterday moaned.
d. The pilot remembered that the lady who said that the man was smelly yesterday moaned.

These results suggest that inhibitory interference is associated with increased processing difficulty when distractors are present, and that such effects can arise due to cue-overload at retrieval. Facilitatory interference has the opposite effect: the presence of a distractor eases, or speeds up, processing.[2] One dependency that is highly susceptible to facilitatory interference is subject-verb agreement. For instance, Wagers, Lau, and Phillips (2009) used self-paced reading and speeded-acceptability judgments to examine the processing of grammatical and ungrammatical agreement dependencies like those in (7):

(7) a. The key to the cabinet(s) unsurprisingly **was** rusty …
    b. *The key to the cabinet(s) unsurprisingly **were** rusty …

Wagers and colleagues found that in grammatical sentences like (7a), the number marking on the plural distractor, e.g., *cabinet(s)*, did not impact rates of acceptance or reading times after the verb. However, in ungrammatical sentences like (7b), the presence of a plural distractor, which matched the number of the verb *were*, increased rates of acceptance and facilitated reading times after the verb, relative to the ungrammatical condition with a singular distractor. Similar profiles have been reported for negative polarity item (NPI) licensing (Drenhaus, Saddy, & Frisch, 2005; Parker & Phillips, submitted-a; Vasishth, Brüssow, Lewis, & Drenhaus, 2008; Xiang, Dillon, & Phillips, 2009; Xiang, Grove, & Giannakidou, 2013), anaphora (Parker, Lago, & Phillips, 2015;

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[2] Some studies call facilitatory interference effects 'attraction' (as in the literature on agreement attraction), or 'intrusion'. Facilitatory interference is an umbrella term for these effects, since they all involve eased or facilitated processing as the result of similarity-based interference.

Parker & Phillips, 2014, submitted-b), and case licensing (Sloggett, 2013). For instance, Parker and Phillips (submitted-b) showed that facilitatory interference arises for reflexive anaphors in sentences like (8), and that such effects can be systematically switched on/off depending on the degree of feature match between the reflexive and target (see also Parker et al., 2015). Likewise, Parker and Phillips (submitted-a) showed that facilitatory interference arises when the NPI *ever* is preceded by a semantically-appropriate licensor, e.g., *no*, in a syntactically-inappropriate position, as in (9) (see also Vasishth et al., 2008), and that the presence or absence of such effects depends on standard memory variables such as the recency of the licensor.

(8) a. *The {librarian | janitor} said that the schoolboys reminded herself about the book.
    b. *The {librarian | janitor} said the the memo reminded herself about the book.

(9) *The journalists [that no editors recommended] (as the secretary noted) ever received compensation.

Facilitatory interference is often described as an *illusion of acceptability*, since it can trick comprehenders into thinking that an ungrammatical sentence is well-formed. Such effects appear distinct from cases of "proximity concord" (Quirk, Greenbaum, Leech, & Svartvik, 1985) or local coherence (Tabor, Galantucci, & Richardson, 2004), as facilitatory interference is observed even when the distractor does not appear between the verb and subject (Wagers et al., 2009), e.g., *The drivers who the runner wave to each morning*. Nor does the effect reflect dialectal variation, since speakers agree on the unacceptability of sentences like (7b) when given ample time. Finally, facilitatory interference cannot reflect misrepresentation of the subject, as has been previously claimed (Bergen & Gibson, 2012; Eberhard, Cutting, & Bock, 2005). Such an account predicts misrepresentation regardless of grammaticality, and therefore predicts "illusions of unacceptability", where sentences with grammatical agreement are misperceived as

ungrammatical. However, illusions of ungrammaticality are rarely experienced (see Phillips, Wagers, & Lau, 2011, for discussion).

The retrieval account proposed by Wagers and colleagues correctly predicts the grammatical asymmetry (Wagers et al., 2009): encountering a plural-marked verb triggers a retrieval process that probes all items in memory in parallel for a match to the required structural and morphological cues, e.g., [+subject] and [+plural]. In sentences with ungrammatical agreement like (7b), the competition between the true subject and the distractor is relatively even, since both items only partially match the retrieval cues. On some portion of trials, the distractor may be incorrectly retrieved due to a partial-match to [+plural], resulting in facilitated processing relative to cases where no plural item is present. In sentences with grammatical agreement, (7a) a distractor that matches only some of the cues is less likely to be mis-retrieved in the presence of a target that matches all of the retrieval cues.

We have argued that both facilitatory and inhibitory interference reflect cue-based direct access retrieval (Dillon et al., 2013; Parker & Phillips, submitted-b; Parker et al., 2015; Wagers et al., 2009; Vasishth et al., 2008; Van Dyke & Lewis, 2003; Van Dyke, 2007; Van Dyke & McElree, 2006, 2011; but cf. Engelmann, Jäger, & Vasishth, submitted). However, recent literature has made the claim that only facilitatory interference effects provide clear evidence about the nature of the cues used in retrieval (see Dillon, 2011; Dillon, Mishler, Sloggett, & Phillips, 2013), since inhibitory interference effects can arise even when the target and distractor overlap in features that are unlikely to be used as retrieval cues (e.g., Gordon, Hendrick, & Johnson, 2001, 2004; Gordon, Hendrick, & Levine, 2002). This point is well-taken, however the same may hold for the interpretation of facilitatory interference effects. For instance, Wagers et al. (2009) suggest in the case of facilitatory interference in subject-verb agreement, retrieval may function as a repair or

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reanalysis mechanism that is engaged when the feature content of the verb does not meet the expectations generated by the subject (see also Parker & Phillips, 2014, submitted-b). Such repair mechanisms, and how they might impact retrieval, remain underspecified. Thus, the diagnosticity of both facilitatory and inhibitory interference with respect to retrieval depend on a more precise formulation of the theory (see Section 3).

In this section, we reviewed evidence about the nature of memory retrieval in sentence comprehension. We noted that items are retrieved at a constant speed, regardless of their position in the sentence representation, the length of the dependency, or the number of distractors, and, that this retrieval is susceptible to interference effects. These findings implicate the use of a direct-access, cue-based retrieval mechanism, and argue against the use of a serial search mechanism, at least for the range of dependencies considered above.

Computational models of direct-access retrieval

Direct-access retrieval can be implemented in a range of general memory models (Clark & Gronlund, 1996), however the primary implemented computational model of sentence processing integrates key concepts from the general cognitive architecture called *Adaptive Control of Thought Rational* (ACT-R; Anderson, 1990; Anderson et al., 2004; Anderson & Lebiere, 1998; Lewis & Vasishth, 2005). In ACT-R, items in a sentence representation are stored as *chunks* in content-addressable memory, and the probability of retrieving an item is governed by the item's level of activation at the time of retrieval, which is expressed as follows[3]:

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[3] Readers familiar with ACT-R may notice our nonstandard presentation. To be clear, we have substituted the expressions for base-level learning and the strength of association into the activation equation, and flipped the sign on the partial match component to emphasize its penalizing nature.

$$(10)\quad A_i = \ln\left(\sum_r t_{ri}^{-d}\right) + \sum_j W_j\left(S - \ln(fan_j)\right) - \sum_k P_k M_{ki} + \epsilon$$

The activation of a memory item i (A_i) is the sum of four terms. The first term is the item's baseline activation, with t_{ri} reflecting the time since the rth retrieval of the item and d a constant, and is intended to approximate the log odds the item will be needed given its usage history. The second term reflects the strength of association between the item and features of the item(s) in the current memory context, each contributing up to a maximum associative strength S but weakened by the number of other items in memory with which it shares features (the *fan*), and weighted by W_j. This term is responsible for inhibitory interference from other available items. The third term is the *partial matching penalty* P_k applied to each cue k in proportion (M_{ki}) to how closely it matches the features of this item. This term is responsible for facilitatory interference. The final term is a noise term drawn from the logistic distribution at each retrieval. By convention both W_j and P_k are constant for all j,k (but see Section 3).

The probability of retrieving an item is a logistic function of its activation with gain $1/s$ and threshold τ, and its retrieval time an exponentially decaying function of activation scaled by a constant F:

$$(11)\quad P(recall) = \frac{1}{1 + e^{(-A_i - \tau)/s}}, T_i = Fe_i^{-A}$$

Note that this latter assumption of the model is not fully consistent with the empirical evidence for a constant-time direct-access mechanism, in which item strength and access speed contribute separately to retrieval times. As such, ACT-R should not be seen as equivalent to the cue-based retrieval theory that we argued for above. Even so, ACT-R is currently the only mathematically precise expression of the cue-based retrieval theory to be applied to

psycholinguistic data to date (e.g., Vasishth et al., 2008; Dillon et al., 2013, 2015). We return to this issue, and discuss other challenges for the current theory in Section 3.

3. Challenges for the cue-based retrieval theory of sentence processing

Having summarized the basic tenets of cue-based retrieval theory and the current state of the computational theory, we now turn to a discussion of current challenges for the theory. We highlight three; some have already been raised in the recent literature and some we discuss here for the first time. We summarize the concerns and offer suggestions for how they might be addressed in order to build a broader theory of the role of memory retrieval in sentence processing.

Challenge 1: **The cue-based retrieval theory lacks a theory of cues.** Linguistic dependencies are subject to a wide range of structural, featural, and interpretive constraints. However, existing accounts of cue-based retrieval are underspecified about how those constraints are mapped onto retrieval cues (Martin & McElree, 2008). One possibility is that there is a direct mapping between the overt linguistic features associated with a dependency, and the cues used in retrieval, such that *all* features associated with a dependency are deployed as retrieval cues. Alternatively, there may not be a uniform mapping between overt features and retrieval cues, such that only a subset of features is deployed as retrieval cues (Dillon, 2011, 2014; Dillon et al., 2013).

Research has used interference effects to diagnose which cues are used in retrieval, based on the assumption that interference is triggered by elements in memory that match the cues used at retrieval. Evidence of interference for a wide range of dependencies, including ellipsis, case, subject-verb agreement, anaphora, and thematic binding suggests that retrieval for each of these

dependencies deploys a combination of morpho-syntactic and semantic cues, as expected if there is a direct mapping between the corresponding grammatical constraints and retrieval cues.

One possible implementation of cue-based retrieval assumes that retrieval cues are combined equally at retrieval, as is typical in models of recognition memory (Clark & Gronlund, 1996). However, it is becoming clear that this is most certainly *incorrect* for language processing as a general rule, as evidenced by a number of studies that have failed to observe interference effects. For instance, Van Dyke and McElree (2011) tested sentences like *The attorney who the judge realized had declared that the witness / the motion was inappropriate compromised …*, where the verb *compromised* selects for an animate subject. Van Dyke and McElree observed greater interference from animate distractors, e.g., *the witness*, than from inanimate distractors, e.g., *the motion*, but only when the distractor appeared in a subject position, i.e., no interference was observed when the distractors appeared in a non-subject position. The authors interpreted these findings as evidence that structural cues, such as *subject*, may be weighted more heavily than non-structural cues at retrieval.

Interference-free retrieval profiles have also been observed for anaphora resolution (Clifton, Frazier, & Deevy, 1999; Cunnings & Sturt, 2014; Dillon et al., 2013; Kush, Lidz, & Phillips, 2015; Nicol & Swinney, 1989; Sturt, 2003; Xiang et al., 2009). For instance, Dillon and colleagues compared subject-verb agreement and reflexive-antecedent dependencies using closely matched sentences, and found that agreement was susceptible to facilitatory interference, but reflexives were not (Dillon et al., 2013). However, as in the Van Dyke & McElree case, it is possible to capture the effects reported for anaphora in a direct-access, cue-based system if one assumes a weighted cue-combinatorics scheme. For instance, Parker and Phillips (2014, submitted-b) showed that reflexives are indeed susceptible to interference, albeit selectively, based

on the degree of feature match between the reflexive and its licensor: when the reflexive mismatched the licensor in just one feature, such as gender or number, there was no interference, but when it mismatched in two features, such as gender and animacy, strong interference effects were found. Such effects could arise only if retrieval engaged both structural and non-structural cues using a weighted cue-combinatorics scheme that weights structural cues more heavily than agreement cues.

There is some evidence that suggests that cue weighting may be attuned to an argument hierarchy. For instance, interference effects are observed for thematic binding when the distractor occurs as an object of a preposition (Van Dyke, 2007), but not when it occurs as a direct object (Van Dyke & McElree, 2011). Similar effects have been reported for other dependencies such as subject-verb agreement. For instance, interference effects for subject-verb agreement ('agreement attraction') are routinely observed when the distractor occurs as an object of a preposition (e.g., Husband & Patson, 2015; Nicol et al., 1997; Pearlmutter et al., 1999; Tanner et al., 2014; Wagers et al., 2009). In contrast, Parker, Shvartsman, and Van Dyke (2015) recently showed that such effects may be more difficult to obtain when the distractor occurs as a direct object (but cf., Clifton et al., 1999; Dillon et al., 2013; and Wagers et al., 2009). These results are consistent with grammatical theories that distinguish core arguments, such as subject and object, from other oblique arguments, such as those contained in preposition phrases (Bresnan, 2001; Chomsky, 1981; Culicover & Jackendoff, 2005; Frazier & Clifford, 1996; Keenan & Comrie, 1977; Pearlmutter, 1983; Van Valin & LaPolla, 1997). According to these theories, core arguments play a more central role at the syntax-semantics interface. If interference profiles correlate with the distinctions made within these hierarchies, this would suggest that cue weighting might be adjusted according to an argument hierarchy.

Cue weighting can be straightforwardly accommodated in cue-based retrieval models (see Taatgen, Lebiere, & Anderson, 2006, for ACT-R; see Van Dyke & McElree, 2011 for additional discussion). More challenging is the implementation of relational syntactic constraints as retrieval cues. Interference effects during dependency formation suggest that the cues used in retrieval are a subset of the features of the target, chosen based on features of the cuing constituent. These item-to-item associations can be computed directly, posing no particular challenge for content-addressable retrieval. However, a relational constraint like c-command is not an item-based feature, as it obtains *between* pairs of items in a hierarchical structure. C-command in particular is central to a range of linguistic constraints on dependency formation, challenging theorists to explain how the cue-based retrieval mechanism appears to reference this relation during incremental structure building.

Some proposals have been suggested for how to implement c-command within content-addressable memory, trading accuracy against computational complexity (see Kush, submitted, for more detailed discussion.). Kush (2013) outlines a retrospective algorithm for exhaustively computing c-command relations in a cue-based system. The algorithm requires that previously encoded items be retrieved and modified as each new word is seen. The complexity of this algorithm scales polynomially in time with the number of words seen. Alcocer & Phillips (unpublished ms.) provide an exact prospective algorithm that carries potential c-commanders forward on each new node, scaling polynomially in space and requiring disjunctive search in memory[4]. If such time or space scaling is reflected in behavior, we would expect to see substantial behavioral differences between early and late parts of sentences, something not at all attested.

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[4] Rick Lewis (personal communication) reports that disjunctive search was considered in the design of ACT-R but rejected because of its poor computational scaling. This likely adds additional time complexity as well.

Approximate algorithms seem to fare better. For instance, one possibility discussed by Alcocer and Phillips would be to decorate memory chunks with "dominance spines", i.e., features that encode the sequence of dominance relations down the rightward branch of a syntactic tree. This approach retains constant-time complexity (though with the addition of one more buffer to hold the spine index), but at the expense of failing to capture some types of c-command relations. Another proposal, suggested by Kush (2013), is that access to c-commanding licensors is mediated by a family of dynamically-updated features that may vary across different dependency types (see also Kush, submitted). According to this proposal items in memory are initially assigned a cue that encodes their 'accessibility' for subsequent retrieval, but this feature can be deleted in response to changes in the shape of the syntactic tree as the parse unfolds. In this system the c-command domain of a quantificational phrase (QP), for example, is represented as follows (Kush, Lidz & Phillips, 2015). When the QP is first encoded, it is assigned a feature {accessible}, which signals that the QP can bind subsequent pronouns. As long as the parser continues to attach structure below the QP, the QP's features remain unchanged. However, if the parser reaches the right-edge of QP's c-command domain (signaled when incremental attachments move higher in the tree), the QP will be retrieved and its {accessible} feature will be removed making it ineligible for future retrieval as a licensor of binding relations. Further work is needed to investigate these algorithms. Particularly illustrative may be finding cases that require computing relations that only some of the above algorithms can capture (see Alcocer & Phillips, unpublished ms., for discussion).

Challenge 2: Current implementations of cue-based retrieval are inconsistent with direct-access. As noted above, the ACT-R implementation is currently the only mathematically precise expression of a content-based retrieval theory to be applied to psycholinguistic data to date (e.g.,

Vasishth et al., 2008; Dillon et al., 2013, 2015). This represents an important challenge for theory development because the use of explicit models accelerates progress by allowing researchers to generate and verify increasingly precise quantitative predictions. While adopting ACT-R's assumptions has been instrumental in developing a cue-based retrieval theory of sentence processing, it also presents a limitation because the resultant quantitative theory is inconsistent with key aspects of the empirical base upon which the cue-based retrieval theory was built. In particular, retrieval speed in the ACT-R model is governed by activation strength, such that items with a higher activation have faster retrieval latencies. This component of the model has been used to explain facilitatory and inhibitory interference effects, where it is assumed that reading times are monotonically related to the retrieval latencies generated by the model (e.g., Lewis & Vasishth, 2005; Vasishth et al., 2008). However, this account is inconsistent with the empirical evidence for direct-access, which suggests that an item's activation strength will impact retrieval accuracy, but not retrieval speed.

Under the standard interpretation of SAT data, the differences observed in reading time measures reflect a convolution of the speed of access and the probability of retrieving an item. This means that reading time data are not adequate indicators of whether retrieval speed differences are present, and by extension, whether direct access mechanisms are employed. Alternative accounts of reading time differences suggest that rather than differences in retrieval speed, as assumed in the Lewis and Vasishth ACT-R model, they reflect either differences in the probability of accessing an item to begin with, or else in the relative ease of integrating an item into the sentence after it has been retrieved. Items retrieved from memory are not interpreted in isolation, but rather must be integrated into the current sentential context, e.g., by modifying the retrieved memory chunk with a feature reflecting its downstream dependency. Importantly, the

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effort required for integration will be governed, in part, by the item's activation strength (Budiu & Anderson, 2004). For instance, retrieval of a low quality representation (defined in terms of activation strength) will make integration slower, giving rise to inhibitory effects. Conversely, retrieval of a higher quality representation will make integration faster, giving rise to facilitatory effects.

Challenge 3: Retrieval models make little contact with empirical and theoretical work on predictive and probabilistic processing. A longstanding body of work in psycholinguistics focuses on the human parser as eager and predictive (e.g. Crain & Fodor, 1985; Fodor, 1978; Garnsey, Tanenhaus, & Chapman, 1989), as well as probabilistic (e.g. Hale 2006; Levy, 2008). Such an idea is not incompatible with the retrieval theory that we've argued for here. For instance, the Lewis and Vasishth (2005) model implements a left-corner parsing strategy that combines bottom-up and top-down parsing. In that model, new information is integrated into a parse tree by retrieiving *predictions* about upcoming information, which are derived from the grammar (see Lewis, Vasishth, & Van Dyke, 2006; Box 1 for an example). It is likely that both bottom-up retrieval-driven and top-down predictive components (probabilistic or otherwise) are in play during sentence comprehension. Preliminary work examining the interaction of the two suggests that expectations can modulate retrieval interference: interference is reduced when semantic properties of the retrieval probe are predictable (Campanelli & Van Dyke, 2016).

More generally, it is likely that the parser deploys predictive and reactive components strategically, in a way that is sensitive to individual-level capacities and task goals. This latter point is in light of converging evidence of strategic and individual variability along these dimensions in other aspects of higher-level cognition (e.g. Einstein & McDaniel, 2005; Braver, 2012), individual

variability in language comprehension skill (e.g. Van Dyke, Johns & Kukona 2014), and strategic adaptation in tasks in both linguistic (e.g. Forster, 1979; Wotschack, 2009; Lewis, Shvartsman & Singh, 2014; Schotter, Bicknell, Howard, Levy & Rayner, 2014) and non-linguistic (e.g. Howes, Lewis & Vera, 2009; Tatler, Hayhoe, Land, & Ballard, 2011) domains. One next stage of theoretical development will be reconciling both styles of processing, and characterizing how and when they are brought to bear, especially with respect to how prediction may impact schemes of cue-weighting, as discussed above.

An additional area for future theoretical work will be to understand the role of probabilistic (not necessarily predictive) processing in retrieval theories. Retrieval theories can possibly implement frequency-based expectations (e.g. Hale, 2006; Levy, 2008) via base-level activation, but would have more difficulty accommodaing evidence that suggests that readers simultaneously entertain multiple parses and update probabilistic representations of the existing parse (e.g. Levy, Bicknell, Slattery & Rayner, 2009; Bicknell & Levy, 2009). Such a theory would either predict that multiple terminals for the current parse are simultaneously represented in memory, and possibly multiple entire prases as well – both with their own retrieval interference implications.

4. Next steps and future directions

In this paper, we advocated the position that linguistic dependencies are frequently resolved using a direct-access, cue-based retrieval mechanism that weights syntactic information more heavily than other information to navigate linguistic representations in memory, and we attempted to address some recent concerns about this position. These concerns fell into three categories: empirical challenges, theoretical gaps, and opportunities for broader explanation. Addressing these concerns is a tall order. But to set the bar lower would be to let the retrieval theory fade into a

niche object, with its own set of theorists, phenomena, and appropriate explanations. As with any field, the study of sentence processing is (or should be) in search of a consensus model, a unified standard theory in its domain and its connection to related fields. We believe that the retrieval theory that we've argued for here can be the core of such a theoretical object, and this position paper outlines an ambitious roadmap in that direction.

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