Hierarchical structure and memory retrieval mechanisms in agreement attraction

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Abstract

Speakers occasionally cause the verb to agree with an element that is not the subject, a so-called 'attractor'; likewise, comprehenders occasionally fail to notice agreement errors when the attractor agrees with the verb. Cross-linguistic studies converge in showing that attraction is modulated by the hierarchical position of the attractor in the sentence structure. We report two experiments exploring the link between structural position and memory representations in attraction. The method used is innovative in two respects: we used jabberwocky materials to control for semantic influences and focus on structural agreement processing, and we used a Speed-Accuracy Trade-off (SAT) design combined with a memory probe recognition task, as classically used in list memorization tasks. SAT allowed us to investigate the full time-course of processing and it enabled the joint measurement of retrieval speed and retrieval accuracy. Experiment 1 first established that attraction arises in jabberwocky sentences, to a similar extent and following the same structure-dependency as in natural sentences. Experiment 2 showed a close alignment between the attraction profiles found in Experiment 1 and memory parameters. Results support a content-addressable architecture of memory representations for sentences in which nouns' accessibility depends on their syntactic position, while subjects are kept in the focus of attention.

Key words: Number, Agreement, Attraction, Syntax, C-command, Memory, Content-addressability, Cue-based retrieval

Introduction

Theories of attraction

Attraction errors are characterized by the incorrect agreement of a target with an element that is not its grammatical controller (e.g., The label on the bottles *are* rusty). The agreement targets are typically verbs, pronouns or adjectives; the attracting elements nouns or pronouns; and the agreement features can be number or gender, although most of the work has concentrated on number attraction in subject-verb agreement. The phenomenon of attraction is directly observable in language production, since it gives rise to a grammatical error, and it is indeed in production that attraction was first theorized (Quirk et al., 1972) and that it was for the most part explored experimentally (Bock & Miller, 1991).

The Marking and Morphing model of agreement production distinguishes between two causes of errors (Bock et al., 2001; Eberhard et al., 2005 and much subsequent work). The first cause lies in the conceptual representation of the subject's notional number. Semantic influences come about during Marking, the process during which the speaker translates the number notion from the message into a linguistic feature. Attraction may also arise at the level of Morphing, due to the influence from the attractor's feature on the highest subject node, by way of a feature percolation mechanism. In this view, each morpheme within the subject phrase is a source of number information with a particular weight, which will determine the strength of its influence on the final number value of the subject phrase. The subject head, having the biggest weight, usually wins in imposing its feature, and the risk of contamination from a modifier situated in the subject phrase depends on the depth of its embedding, which defines the length of the path it has to percolate. This accounts for the fact that, when attractors are more deeply embedded, they trigger less attraction, as shown by Bock & Cutting (1992), who compared attractors situated in a relative clause attached to the

subject head to those situated in a subject PP modifier (e.g., Bock & Cutting, 1992). It also accounts for the fact that elements situated higher in the subject phrase ('flights' in *The helicopter for the flights over the canyon are low*) generate more errors than those situated lower ('canyons' in *The helicopter for the flight over the canyons are low*) (Franck et al., 2002).

Although most studies have focused on attraction from prepositional phrase modifiers situated in the subject phrase, various studies have shown that nouns that are not in preverbal position may also trigger attraction. For example, attraction was found with plural objects in the production of various involving movement of the object in preverbal position, like in object relatives (Kimball & Aissen, 1971; Bock & Miller, 1991; Franck et al., 2010; Santesteban, Pickering, & Branigan, 2013), object clefts (Franck et al., 2006) or object questions (Franck et al., 2015). In these structures, the attractor disturbs agreement even though the object is not part of the subject phrase and the subject and the verb are contiguous in the linear word string (e.g., 'patients' in *John speaks to the patients that the medicine cure*). These attraction errors are left unexplained by Marking and Morphing. The possibility that any element in the sentence may attract verbal agreement may nevertheless be captured by the hypothesis that attraction arises from the erroneous operation of a process responsible to retrieve the agreement controller from memory (Badecker & Kuminiak, 2007; Wagers, Phillips & Lau, 2009). This hypothesis capitalizes on a wide array of findings in the sentence comprehension literature showing the role of memory in the processing of sentences with long-distance dependencies, and more particularly the involvement of a cue-based retrieval process sensitive to similarity-based interference (e.g., Gordon et al., 2001; Lewis & Vasishth, 2005; Lewis, Vasishth, & Van Dyke, 2006; McElree, Foraker, & Dyer, 2003, see next section). Badecker & Kuminiak argued that a similar process is at play in agreement computation during production: in order to inflect the verb with agreement, the subject needs

to be retrieved from memory, a process that is guided by cues to subjecthood (e.g., nominative case, occupying a specifier position in the extended projection of the verb phrase, being pre-verbal, etc.). The presence, in memory, of an element bearing some similarity to the subject is the cause of an occasional erroneous retrieval of that element as the controller of agreement. In this view, attraction can potentially arise from any element in the sentence if that element bears some similarity with the subject. In this view, object attraction is expected to arise when the object has been moved preverbally since it is therefore available in memory when agreement needs to be computed. Moved objects are similar to subjects in that they are NPs, bear agreement features, occupy a similar phrase structure position (a specifier) and the typical sentence-initial position of subjects.

The hypothesis that cue-based retrieval is involved in the processing of agreement gained supported by studies of agreement in sentence comprehension. A number of studies using self-paced reading, eye-tracking and ERP methods have reported strong attraction effects taking the form of an illusion of grammaticality: the presence of a plural attractor noun mismatching the singular head decreases the perturbation typically found in ungrammatical sentences when encountering the plural verb linked to a singular subject. The facilitatory effect of a mismatching attractor was consistently reported in ungrammatical sentences (Wagers, Lau & Phillips, 2009; Tucker & Wagers, 2010; Dillon et al., 2013; Tanner, Nicol & Brehm, 2014; Lago et al. 2015), while its effect was weak or absent in grammatical sentences. Wagers et al. (2009) argued that the existence of an effect-size asymmetry between grammatical and ungrammatical sentences was the signature of a cue-based retrieval process in comprehension, supported by the same basic memory mechanisms as Badecker & Kuminiak (2007) proposed for production. According to this view, the agreeing verb in comprehension supplies retrieval cues to check for a controller NP in the parse. Such cues are expected to include information about the grammatical number of the candidate NP as well as

its case or syntactic position. If the clause-mate subject NP does not match the verb in number, then no single NP will fully match the retrieval cues. But the presence of a plural attractor in the parse would partially match the cues, allowing the parser to (erroneously) satisfy the agreement requirement on some proportion of trials. When a subject NP that matches the verb is present, then the correct controller of agreement will fully match the cues and any attractor will only partially match it. Correspondingly, attraction in grammatical strings is expected to be weaker compared to attraction in ungrammatical strings. These predictions were borne out by computational simulations in ACT-R (Dillon et al., 2013).

In sum, recent accounts of attraction have highlighted the role of a cue-based retrieval mechanism in both sentence production and comprehension. But what do we know about the memory system that underlies sentence processing?

Memory for sentences

There is considerable evidence that access to information in long-term memory is mediated by some form of content-addressability (McElree, 2006, Jonides et al. 2008), in which cues to the target memory are compiled at the retrieval site based on a subset of the relevant information available when memory is queried. The cues make contact to those memory representations in a global fashion (Clark & Gronlund, 1996): the degree to which the cues match or are associated with target memories is evaluated simultaneously across all representations in memory, without recourse to a sequence of searches through irrelevant memories (cf. McElree & Dosher, 1989). The efficacy of this process is determined by whether there are encodings that match cues, how strongly they match the cues, and how uniquely they do so (Nairne, 2002). Ideally, the cues would distinctly point to only the relevant, desired items.

An important source of evidence implicating content-addressability comes from studies showing that retrieval time is independent of the number of items in memory. The response-

signal speed-accuracy trade-off (SAT), a procedure that investigates the full time-course of processing, enables joint measurement of retrieval speed and retrieval accuracy (Wickelgren, 1976, McElree & Dosher, 1989). In a probe recognition task, participants are trained to respond to a signal presented at varying time points after the onset of the recognition probe, spanning the full time course of retrieval between about 100 ms to 3000 ms. In this task, accuracy is shown to be a function of retrieval time with the following typical phases: an initial phase of chance level performance, followed by a phase of increasing accuracy, followed by an asymptotic period (McElree, 2006). The asymptote provides a measure of the overall probability of correct retrieval, since additional time does not improve performance. Retrieval speed is measured by the intercept of the function, indicating when information first becomes available, and by the rate of rise, indicating the rate at which accuracy grows from chance to asymptote. These two parameters provide key indicators of the dynamics of retrieval, independently of the quality of memory representations.

In typical probe recognition tasks in which the SAT function is measured for judgments on each serial position in the list, asymptotic accuracy is a smoothly-varying function of position in the list (McElree & Dosher, 1989; McElree, 1998): the asymptote decreases gradually with recency of list position. On the other hand, dynamics parameters are typically not smoothly varying and instead show a simple bifurcation. For word lists, the most recent word usually enjoys a dynamics advantage over all other words (McElree & Dosher, 1989), but the other words do not vary in terms of their retrieval speed. This has been taken as evidence for a bipartite architecture for working memory: most information remains in long term memory, while a focus of attention allows privileged access to a restricted set of representations (Cowan, 2001; McElree, 2006, see Wagers & McElree, 2013 for a review).

While research on word list memorization indicates the involvement of a cue-based retrieval mechanism (McElree & Dosher, 1989; McElree, 1996; Oberauer, 2009; Oztekin &

McElree, 2007), this is only true if the task can be solved using only the content of individual words in the list; for example, in a probe recognition task. When relational information is explicitly tested, i.e., when temporal or spatial order has to be retrieved, then retrieval dynamics vary with list size or item position, suggesting that the items in memory are searched in a sequence (Gronlund et al., 1997; McElree, 2001; McElree & Dosher, 1989). This raises the question of how findings from list memory experiments translate to sentences. Sentence processing often requires accessing an element situated at a distance from its dependent; for example, retrieving the subject or the object of the verb. However, sentences critically differ from lists in that they involve relations between words, organized within linearized hierarchical structures. One might therefore expect order information to play a key role in sentence processing, and therefore a mechanism of search to be involved. Nevertheless, two types of evidence also point to the involvement of a direct-access, cue-based mechanism in the processing of long-distant dependencies in sentences, rather than a search mechanism (e.g., Lewis & Vasishth, 2005; McElree, 2000; 2006; McElree, Foraker & Dyer, 2003; Lewis et al., 2006; see Parker, Shvartsman & Van Dyke, 2017).

The first kind of evidence comes from SAT studies of sentences, where it is found that retrieval speed is independent of the length of the dependency. In such studies, participants read sentences presented one word at a time, in Rapid Serial Visual Presentation (Potter, 1984). After the final word, they make a binary acceptability judgment that depends on correctly retrieving a grammatical dependent of the word. In McElree (2001) and McElree (2003) Experiment 1, the final word was a verb, which had to be paired with a displaced object. For example, compare (1) to (2):

(1) It was the **scandal** that the celebrity relished/*panicked.

(2) It was the **scandal** that the model believed that the celebrity relished/*panicked.

In both of these sentences, it is necessary to retrieve the object (bolded above) to discriminate between acceptable continuations and unacceptable ones, marked here with a star. This parallels probe recognition studies of word lists, except the nature of the probe, i.e., the verb, is itself quite different: it requires identifying an element it stands in a particular syntactic relation with. Nonetheless, McElree (2001) and McElree (2003) both found that the results were strikingly similar to word-list memorization studies: the distance between the probe and the target affected the asymptotic accuracy of the acceptability judgment task but processing speed was constant. The speed of retrieving a displaced object seems to be independent of the distance and the number of distractors that separate it from the verb. Similar findings have been made for the resolution of pronouns (Foraker & Dyer, 2007) and of ellipsis (Martin & McElree, 2008, 2009). Studies of subject-verb dependencies are also generally consistent with this picture, with one exception: when the subject and verb are linearly adjacent, they can be linked more quickly than when they are separated (McElree, Foraker & Dyer, 2003, Wagers & McElree, 2013; compare: *The editor laughed/*ripped* v. *The editor that the book amused laughed/*ripped*). This adjacency advantage is akin to a focus-of-attention effect: when no other clauses intervene between subject and verb, the subject remains in the focus of attention.

The second type of evidence supporting direct, content-based access to memory during sentence processing is that retrieval accuracy is sensitive to similarity-based interference. Various studies have shown that the presence of distractors sharing some of the features of the target to-be-retrieved penalizes sentence processing. Dual-task studies in which participants are asked to memorize a list of words while reading a sentence show longer reading times and decreased comprehension accuracy when the distant target shares semantic/referential properties with words from the list (e.g., Fedorenko, Gibson & Rohde, 2006; Van Dyke & McElree, 2006). Various studies also showed effects of similarity between target and

distractors within the sentence. Evidence from SAT and eye-tracking experiments converges to show that semantic similarity affects the processing of long-distance dependencies (e.g., Ferreira, 2003; King & Just, 1991; Lewis, 1996; Stolz, 1967; Van Dyke & McElree, 2011). Also, the processing of long-distance dependencies in the presence of distractors that are semantically similar to the target is harder and sometimes even impossible (e.g., center embedding), unless additional distinctive cues, like for example case markers, are present allowing to overcome the strong semantic overlap (Lewis, 1996). Syntactic similarity also plays a role: a constituent intervening between the subject and the verb triggers significantly more interference when it also occupies a subject position (in a relative clause) compared to when it occupies a non-subject position (e.g., Van Dyke, 2007; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2011; Arnett & Wagers, 2017). Importantly, when experimental measures allowed teasing apart accessibility and the dynamics of retrieval through the SAT methods, evidence shows that semantic and syntactic similarity affect the accessibility of the element to be retrieved, but not the speed with which it is retrieved. This, again, supports the hypothesis that constituents are retrieved on the basis of their content, by way of a cue-based retrieval mechanism.

In sum, research on memory underlying sentence processing has revealed an important role for a cue-based retrieval mechanism in the processing of long-distance dependencies. Evidence shows that the probability of correctly accessing an element previously encountered in the sentence depends on how closely its syntactic and semantic content matches the retrieval probe (i.e., a verb that element relates to) and on how closely other distracting elements in memory match it. Like list memorization, representations may occupy two different states: a passive state and an active state within the focus of attention. Sentential subjects stay in the focus of attention when they are adjacent to their verb, but may be shunted from the focus of attention when material intervenes. The exact conditions that underlie such

shifts remain to be precisely determined (Wagers & McElree, 2013). Crucially, there is little evidence that a search mechanism is deployed, even when order is relevant to parsing (McElree, Foraker & Dyer, 2003, Experiment 3; but see Dillon et al. 2013).

Overview of the study

The present study explores the relation between the structural conditions of attraction and memory by testing the hypothesis that elements that trigger high rates of attraction do so because they are easier to retrieve from memory than those that trigger lower rates of attraction. Noun phrases' availability and the dynamics of their retrieval were measured by way of a standard memory task, i.e., probe recognition, and linked to attraction rates. We investigated two structures previously studied with natural sentences, each containing two attractors: complex subject modifiers involving two PPs and complex object questions involving a moved object head and its PP. In these structures, the two attractors were found to give rise to different degrees of attraction in sentence production. As already discussed above, in the presence of two PPs, the hierarchically higher one generates more interference than the lower one (Franck et al., 2002). Similarly, in complex object questions, attraction from the head of a moved complex object, situated higher in the tree ('patients' in **Quelles patientes du médecin dis-tu que l'avocat defendent?* *Which patients of the doctor do you say that the lawyer defend?) is stronger than attraction from the same lexical element when it is in a lower position of modifier of the head ('patients' in **Le médecin de quelles patientes dis-tu que l'avocat defendent?* *The doctor of which patients do you say that the lawyer defend?). The relevance of testing these two structures lies in a key difference with respect to the structural position of their higher attractor. In complex object questions, the hierarchically higher object head occupies a special position of c-commanding the verb (Reinhart, 1976; Chomsky 2000): a node X c-commands Y iff Y is dominated by the sister node of X. The c-commanding relation has consequences on a variety of morphosyntactic and interpretive processes,

including agreement (but also the binding of anaphors, the determination of quantifier scope, etc.). In contrast, in sentences with double modifiers, the two PPs occupy positions that linearly precede the verb, without entertaining any structural relation to it.

Our aim was to determine whether the attraction potential of hierarchically higher elements (highest PP, c-commanding object head) aligns with their accessibility/speed of access from memory, which would attest of a direct link between attraction and memory, a piece of evidence that has not yet been shown. To reach that goal, we designed two experiments on the processing of sentences in a semi-artificial jabberwocky language in which pseudo-nouns replaced nouns, while function words and verbs were real words of the French language. The aim of using jabberwocky was to explore the influence of structural factors on memory, and control for semantic influences on attraction, given the known influence of semantic factors like the notional plurality of the sentence (e.g., Eberhard, 1999; Foote & Bock, 2012; Smith, Franck, & Tabor, 2018; Vigliocco, Butterworth & Garrett, 1996), but also the semantic similarity between the subject and the attractor (Barker, Nicol & Garrett, 2001) and the semantic plausibility of the attractor as being an agent (Hupet, Fayol, & Schelstraete, 1998). Using pseudo-nouns while preserving verbs and the grammatical skeleton of natural sentences prevents participants from building a rich semantic representation for the sentence while still allowing them to build a parse tree and computing the agreement dependency without difficulty. Moreover, given our interest in the memory retrieval processes for the noun phrases in the sentence, it was important to control for their lexical frequency, given its well-known influence on memory retrieval (e.g., (Mulligan, 2001) and sentence processing more generally (e.g., (MacDonald, Pearlmutter, & Seidenberg, 1994). The first structure tested involves complex object questions, in which the object consists of a head and a PP modifier, as illustrated in (3). The second structure tested involved double PP modifiers,

as illustrated in (4). The position of the mismatching plural feature was either on the hierarchically higher attractor, as in (3a) and (4a) or on the lower one, as in (3b) and (4b).

(3) a. Quels dafrans du brapou dis-tu que le bostron defend?

Which-P dafrans-P of the-S brapou-S do you say that the-S bostron-S defends-S?

b. Le brapou de quels dafrans dis-tu que le bostron defend?

The-S brapou-S of which-P dafran-P do you say that the-S bostron-S defends-S?

(4) a. Le bostron des dafrans du brapou dort.

The-S bostron-S of the-P dafrans-P of the-S brapou-S sleeps-S.

b. Le bostron du dafran des brapous dort.

The-S bostron-S of the-S dafran-S of the-P brapous-P sleeps-S.

Experiment 1 examines whether attraction arises in jabberwocky, and whether it shows sensitivity to structure as found in natural sentence production. We used a speeded grammaticality judgment task, which has been shown to consistently replicate attraction and its syntactic modulation found with the sentence completion task (Franck et al., 2015). If the structural component of attraction is syntactic in nature and independent of the semantic content of the words and their relationships, we expected to replicate the findings from natural language in our jabberwocky materials: (a) generally more errors and/or slower response times in the presence of a mismatching plural attractor, and (b) stronger attraction from a plural attractor situated high and/or c-commanding the verb than from a plural attractor situated low and intervening by precedence on the agreement relation. To anticipate, attraction was found in both structures. It was stronger for the c-commanding attractor than for the preceding one in object questions, but a similar attraction rate was found for the two PP attractors in the double modifier condition.

Experiment 2 tests the ease with which the noun phrases of the sentence, i.e., the subject and the two attractors, are retrieved from memory. The study uses a procedure combining a

probe recognition task at the end of the sentence with the Speed-Accuracy Trade-Off design (McElree & Dosher, 1989). Participants saw the sentences word by word in Rapid Serial Visual Presentation mode, followed by the presentation of a pseudo-noun (the probe) that could either be the subject, the higher attractor, the lower attractor or a foil. Participants judged if the probe occurred in the sentence at each of 18 tones presented at 250 ms intervals after the onset of the last word (the verb). Response accuracy was thus measured across the full time-course of retrieval and discriminative speed-accuracy curves were estimated. This procedure is similar to that used in studies using SAT to explore list memorization (e.g., McElree & Dosher, 1989; McElree, 1996; 1998), but contrasts with studies that have made use of the SAT procedure in sentence comprehension, which involve an acceptability judgment task at the sentence-final verb where a syntactic dependency is established (e.g., retrieving a displaced object or integrating a distant subject, McElree et al., 2003; Van Dyke & McElree; see Wagers & McElree, 2013 for a review). In these sentence studies, the task involves not only the memory retrieval of the distant element, but also various processes at play in judging whether the sentence is acceptable or not. Here, the use of the probe recognition task provides a purer measure of how well and how fast an element from the sentence is retrieved from memory.

The use of the SAT paradigm was expected to inform us about two aspects of items in memory: the overall strength or accessibility of that item, which we link to the construct of activation in ACT-R (Lewis & Vasishth, 2005) and the speed with which that item can enter the processing stream, which has been linked to the concept of focus of attention (McElree, Foraker & Dyer, 2003). Because judgments about a probe are collected across an extended time-span, it is possible to estimate the function that relates task performance to time elapsed. As a consequence, it is possible to determine the maximum attainable accuracy for a task and

the rate at which information accrues. A good model of typical SAT data is given by the shifted exponential function below, in which performance is measured by d-prime (d′):

$$d' = f(t) = \begin{cases} \lambda(1 - e^{-\beta(t-\delta)}), & t > \delta \\ 0, & t \leq 0 \end{cases}$$

This equation can be understood by identifying three periods in task performance:

- A period of chance performance, indexed by the intercept parameter δ (ms);

- A period of increasing accuracy, indexed by the rate parameter β (ms^{-1});

- A period in which performance approaches its limit, indexed by the asymptote parameter λ (unitless).

The first two parameters (□, □) serve as a joint measurement of memory access dynamics, and can be used to ask whether certain items in memory take characteristically longer on average to access (McElree, 1998, McElree, Foraker & Dyer, 2003). The inverse of the rate parameter β is the function's time constant, and when $t = \frac{1}{1/\beta} + \delta$ (ms), then d′ has achieved approximately 63% of asymptotic accuracy (or, exactly $100 \cdot (1 - e^{-1})\%$). The asymptote parameter □ relates to the availability or strength of an item in memory, which controls the maximum attainable task performance.

If our hypothesis is correct that memory access for elements from the sentence operates on hierarchical representations and that agreement/attraction is tightly linked to the properties of items in memory, then we expect the following:

- Subject heads, with which agreement is usually computed correctly, should be more accessible (higher □) and/or retrieved earlier/faster (lower □, higher □) than the two attractors, regardless of their position in the linear word string;

- Attractors that trigger high attraction, expected to be those in a hierarchically higher position and/or occupying a c-commanding position with regard to the verb, should be more accessible (higher □) and/or retrieved earlier/faster (lower □, higher □) than those that trigger weaker attraction;

- The higher attraction expected for c-commanding attractors could either be accounted for in terms of cue-based retrieval, under the assumption that elements from a c-commanding domain have a special cue coding for it, or in terms of search, under the assumption that the c-commanding domain of the verb would be searched first. If cue-based retrieval shapes this syntactic modulation on attraction, the difference between the c-commanding object head and its modifier should manifest on the accessibility/strength of these elements (□), which should be higher for the former, being more similar to the to-be-retrieved controller. If, rather, a search mechanism underlies the effect, the difference between the c-commanding object head and its modifier should manifest in the dynamics parameters (□, □), and the c-commanding element should be retrieved faster than its preceding modifier.

Experiment 1: Attraction in jabberwocky

Method

Participants

Forty-three participants took part in the experiment. They were all native French speakers aged between 20 and 40 with no reported hearing or language impairment. They received course credit for their participation. The study was approved by the Ethics committee of the University of Geneva, and participants signed written consent forms.

Materials

Experimental materials consisted of jabberwocky sentences containing pseudo-nouns, real grammatical words and real verbs. Pseudo-nouns respected phonotactic constraints of the French language, and their resemblance to existing words was minimized. A total of 192 items varying along 4 dimensions were created: Structure, characterizing the nature of the attracting element (Object vs. Modifier); Height, characterizing the position of the attractor

noun varying in number (Low vs. High, with the additional specificity of object heads being not only high but also c-commanding the verb); Match, characterizing the number match between the head and attractor nouns (Match vs. Mismatch); and Grammaticality (Grammatical vs. Ungrammatical). Whereas transitive verbs were used in the Object condition, intransitive verbs were used in the Modifier condition. In the Object condition, we controlled for the position of the *wh*-element such that it always appeared in the NP containing the plural feature (whether high or low). All subject heads were singular. Structure was manipulated between-items while Height, Match and Grammaticality were manipulated within-items. Examples of items in the different experimental conditions are provided in Table 1.

Table 1. Examples of items in the different experimental conditions formed by the crossing of Structure, Height and Grammaticality (only conditions of number mismatch are illustrated).

Structure	Height	Example
Modifier	High	Le bostron des dafrans du brapou dort/*dorment The bostron of-the-pl dafrans of-the brapou sleeps/*sleep
	Low	Le bostron du brapou des dafrans dort/*dorment The bostron of-the brapou of-the-pl dafrans sleeps/*sleep
Object	High	Quels drafrans du brapou dis-tu que le bostron defend/*défendent? Which dafrans-pl of-the brapou do you say that the bostron defends/*defend?
	Low	Le brapou de quels dafrans dis-tu que le bostron defend/*défendent? The brapou of-which-pl dafrans-pl do you say that the bostron defends/*defend?

Items were distributed across 4 lists and each list contained two versions of an item. There were 48 experimental items in total, combined with 48 fillers of the same type as the experimental ones, whose subject heads were all plural and which varied in Structure, Height, Match and Grammaticality (all between-items).

Procedure

Materials were presented on a computer screen using the E-Prime software. Sentences were split in windows corresponding to phrases. Windows were presented for a fixed period of 500 ms, except at the verb, i.e., the final word of the sentence. These rather long presentation times were selected to minimize judgment errors, and avoid a possible trade-off between speed and accuracy. Grammaticality judgment times were measured at the verb onset. Participants were asked to judge the grammaticality of the sentences as quickly as possible and press on the corresponding response button. The experimenter illustrated the task by presenting 6 example sentences and explaining why they could be considered grammatical or ungrammatical. Participants had no difficulty understanding the task. The experiment started with 6 practice trials. Having the next item appear as soon as the participant had answered imposed a sustained rhythm. A pause was introduced in the middle of the experiment.

Analysis

Participants gave no response on approximately 11% of trials and these trials were removed from further analysis. The no-response trials were uniformly distributed across Match, Height and Grammaticality factors; but there were significantly more no-response trials for Object structures than for Modifier structures ($\square^2(1) = 28$, $p < .001$). One participant was removed for very low accuracy across the entire experiment (69%, which was greater than 2 standard deviations from the mean accuracy on the logit scale).

To analyze the extent of attraction for a given sentence type, we computed an Attraction Index. For each combination of Structure, Height and Grammaticality within an item, we converted error rates into logit scores (using the log-linear correction for zeroes). We then subtracted the Match score from the Mismatch score, yielding a positive index for a given item when there was attraction. Response times (RTs) were measured from a window beginning at the offset of the verb.

Mixed-effects regression models of dependent variables (Attraction Index, log RTs) were carried out on the experimental factors (Structure, Height, Grammaticality; and Match for RTs), all of which were sum-coded to (+1/2, -1/2) with the following levels having positive valence: Structure*:Modifier,* Height*:High,* Grammaticality*:Ungrammatical*, and Match:*Mismatch*. Maximal random effects were estimated where possible and, where the model failed to converge, we attempted to include critical slopes (Barr et al., 2013). Models were estimated using the *lme4* package in R (Bates, Maechler, Bolker & Walker, 2015); *p*-values are reported from the *lmerTest* package (Kuznetsova, Bruun Brockhoff, & Haubo Bojesen Christensen, 2016) using the Satterthwaite approximation.

Results

Attraction was present for both Object and Modifier jabberwocky sentences. The overall error rate was 7%, ranging from less than 1% for High Object Match conditions up to 16-18% in Object and Modifier Mismatch conditions. The average Attraction Index scores on accuracy are shown in Fig 1. Overall, the average Attraction Index is positive ($\beta_0 = 0.69$, t = 6.4, $p < .001$), indicating more errors in Mismatch sentences, i.e., ones with a plural attractor. We found a marginal effect of Height ($\beta_{Height} = 0.40$, $t = 1.8$, $p < .10$), consistent with High attractors causing more attraction than Low attractors. But this was qualified by a significant interaction between Structure and Height ($\beta_{Hght\ x\ Strctr} = -1.0$, $t = -2.4$, $p < .05$). We conducted two separate simpler models to clarify the interaction, in each one looking only at one level of

Structure. In Object structures, there was an effect of Height with more attraction for High, c-commanding attractors compared to Low attractors ($\beta_0 = 0.55$, $t = 3.6$, $p < .001$; $\beta_{Height} = 0.90$, $t = 2.9$, $p < .01$). In Modifier structures, there was no effect of Height ($\beta_0 = 0.83$, $t = 5.6$, $p < .001$; $\beta_{Height} = -0.11$, $t = -0.38$, *n.s.*). No other factors were significant.

Fig 1. Attraction index scores in accuracy (mean and standard error) in Experiment 1. The attraction index was computed by converting <item,condition> error rates into logits, and subtracting the match score from the mismatch score.

RTs paint a more complex picture, and they are reported in Fig 2. We only analyzed correct responses, because there were relatively few error trials. So although these are trials in which participants did not make an error in their overt response, their RTs did indicate that a Mismatching attractor influenced the grammaticality judgment. Participants took longer to judge Mismatch conditions than Match conditions ($t = 4.5$, $p < .001$); longer to judge Ungrammatical conditions ($t = 3.4$, $p < .001$); and longer to judge Modifier conditions ($t = 2.3$, $p < .05$). There was a significant interaction of Structure with Grammaticality ($t = 2.2$, $p < .05$) and a marginal interaction of Structure with Height ($t = -2.0$, $p < .10$). Finally there was a significant three-way interaction of Match, Structure and Height ($t = -2.8$, $p < .01$).

Fig 2. Mean Judgment RTs in Experiment 1. Error bars report standard error over items.

To make sense of the significant three-way interaction of Match, Structure and Height, we computed an RT Attraction index for each <Subject, Structure, Height> tuple by subtracting RTs in the Match condition from RTs in the Mismatch condition, thus showing how much a plural attractor disrupted judgment. The results of this analysis are given in Table

2. The average attraction cost was 193 ms ($t = 6.4$, $p < .001$). There was a significant Structure x Height interaction (213 ms, $t = 2.1$, $p < .05$). This analysis reveals that Mismatch conditions imposed a cost on judgment times (the index is systematically above 0), and that cost was influenced by attractor height differently in the two structures: in line with the accuracy measure, high attractors engender the greatest attraction cost in Object structures, but in modifier structures, low attractors give rise to the greatest attraction cost, where no difference was found in the accuracy measure.

Table 2. RT Attraction index scores in Experiment 1.

Structure	Height	Attraction index
Modifier	High	129 ms (s.e. = 51 ms, n = 40)
	Low	280 ms (s.e. = 55 ms, n = 40)
Object	High	213 ms (s.e. = 62, n = 39)
	Low	153 ms (s.e. = 62, n = 39)

Discussion

There are four key findings from Experiment 1. First, attraction arises in jabberwocky sentences, in which semantics plays virtually no role. Participants made more errors in judging the grammaticality of sentences containing a plural attractor that mismatched the number of the head noun, than in sentences containing two singular nouns. Accuracy was similar to that found in natural languages – above 80% – suggesting that participants had no difficulty in judging the grammaticality of jabberwocky sentences. This finding supports the view that attraction arises independently of semantic factors, even if such factors were found to also contribute to attraction (Barker et al., 2001; Hupet et al., 1998; Thornton & McDonald, 2003).

Second, attraction was stronger and grammaticality judgment times were slower when the mismatching plural noun was the head of a moved complex object, compared to when it was embedded in that constituent. Remember that in both cases the attractor was the question word or *wh*-phrase, and thus the information-structural focus of the sentence; hence, the two conditions are comparable in that regard. In High conditions, the mismatching plural phrase c-commands the verb, whereas in Low conditions, it does not; it only precedes it. This finding replicates natural language data obtained with the same structures (Franck et al., 2015), as well as other reports showing that c-commanding elements have a stronger attraction potential than preceding ones (Franck et al., 2006; 2010; Mirdamadi, Kahnemuyipour & Franck, 2017) and suggests that the hierarchical effects on attraction are a product of syntactic structure.

Thirdly, in the double modifier condition, both attractors generated similar rates of attraction. This finding contrasts with natural language data showing stronger attraction with the highest attractor (Franck et al., 2002; Gillespie and Pearlmutter, 2011). A first difference between these two data sets lies in the task procedure: whereas natural data were obtained with sentence completions, jabberwocky data were obtained with grammaticality judgments. However, the task does not appear to be responsible for the difference: grammaticality judgments on natural French sentences give rise to stronger attraction with the highest PP (Franck & Wagers, 2015), replicating results obtained with a sentence completion procedure. Another key difference between jabberwocky and natural language lies in the absence of lexical semantics in the former. As a result, two syntactically correct structures can be built in double PP conditions: one in which the second PP is adjoined to the entire subject phrase, and one in which it is nested inside the first PP. Semantics in the materials from Franck et al. (2002) promoted the nested type, so that the second PP was embedded in the first PP. The lack of semantic information in the jabberwocky materials may have promoted more instances of the first type, in which the second PP modifies the subject directly. If this were the case,

both PPs would be at the same syntactic distance to the head, which would explain the lack of a height effect.

Finally, attraction was found for both grammatical and ungrammatical sentences, in line with other studies that used a grammaticality judgment procedure in French (Franck et al., 2015), but in contrast to a variety of online sentence comprehension studies using eye-tracking, ERP, and self-paced reading, in which the presence of a mismatching feature only affected ungrammatical sentences (Dillon et al., 2013; Tanner et al., 2014; Wagers et al., 2009, see Jäger, Engelmann & Vasishth, 2017, for a meta-analysis). This point is addressed in the General discussion.

Experiment 1 shows that attraction arises in a jabberwocky language, providing us with a tool to explore attraction with minimal influences from the semantics. It also shows that attraction with jabberwocky sentences is sensitive to the key distinction between precedence and c-command intervention, since the c-commanding attractor in object questions generated more attraction than the preceding one. The next step in exploring the links between attraction and memory is now to determine whether the strength of attraction found in Experiment 1 is a function of the ease with which the attractor is retrieved from memory, which is the aim of Experiment 2.

Experiment 2: Accessibility in memory and attraction

Methods

Participants

Twenty-five participants took part in the experiment. They were all native French speakers, with ages ranging between 20 and 40, with no reported hearing or language impairment. They received course credits for their participation. The study was approved by

the Ethics committee of the University of Geneva, and participants signed written consent forms.

Materials

A total of 432 experimental items were created, organized into 36 item sets defined by the crossing of three variables: Structure (Object vs. Modifier), Probe (Subject vs. High attractor vs. Low attractor), and Probe status (Target vs. Distractor). Each item therefore appeared in 12 conditions. The sentences contained the same pseudo-nouns as Experiment 1. All sentences were grammatical, and they always contained one plural feature (there was no match condition). The position of the plural feature was counterbalanced on the three NPs (Subject, Attractor high, Attractor low). Distractor words used for the probe recognition task were taken from the list of pseudo-nouns used for building the sentences, such that interference could occur across the board from previously seen sentences. The selection of distractor words associated to each item was randomized.

A total of 216 additional filler items were created, also spread in 18 sets of 12 variants of each item, following the same design as experimental items. Filler items were all ungrammatical with respect to agreement. They represent 1/3 of the total items. The 648 items (432 + 216) were distributed in 6 lists of 108 items each.

Procedure

The multiple-response SAT procedure was used to estimate accuracy as a function of time (Wickelgren, Corbett & Dosher, 1980, Martin & McElree, 2008). Trials began with a 1-second fixation cross in the center of the display. Sentences were presented word-by-word in rapid serial visual presentation mode (Potter, 1988). Word stimulus onset asynchrony varied by word length according to the formula: SOA=ArgMax(190 ms + 25 ms/char, 400ms). Inter-stimulus interval was constant at 100 ms. Fifty ms after verb offset, participants were probed with a word that was either one of the three NPs of the sentence or a distractor word not in the

sentence. Fifty ms after the visual presentation of the probe, a series of 18 tones was presented. Each 1000 Hz tone was 50 ms in duration and there was a lag of 350 ms between them. Participants were trained to press the button 'yes' if the probe was in the sentence, or 'no' if it was not. Starting from the first tone, they were trained to press the two response buttons simultaneously until they had decided whether the probe was in the sentence. Right after the probe recognition task, participants were required to perform a grammaticality judgment task and judge if the sentence was grammatical or not, again by button pressing. This additional task was only added to ensure that participants would fully parse the sentence rather than develop a strategy of simply memorizing the pseudo-nouns, which was sufficient to perform probe recognition. Hence, results to that task were not analyzed.

Participants came to the lab four times. The first session was dedicated to training. They were familiarized with jabberwocky sentences and the possible occurrence of agreement errors. They were then presented with the instructions, and progressively trained to respond contingently to the tones. The participants received feedback if they took longer than 200 ms to begin responding, if the first two responses were not simultaneously executed, or if they gave fewer than 16 total responses within 6000 ms. The next three sessions were dedicated to running the experiment proper. Two lists were presented per session, separated by a break. A session lasted about 20 minutes.

Analysis

For each participant, we calculated accuracy at each response tone. A d′ score was calculated by first transforming accuracy scores by the inverse normal distribution function. The resulting Z-score of the false alarm rate, i.e., percent incorrect for Distractors, was subtracted from the Z-score of the hit rate, i.e., percent correct for Targets (MacMillan & Creelman, 1991). Lag-latency was calculated by adding the average response time at each

response tone to tone latency. The resulting d′/lag-latency series was fit by a saturating, shifted exponential function:

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

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

This function is described by three parameters: an asymptote, λ; a rate, β; and an intercept, δ. The λ parameter describes maximum achieved performance. The speed of processing is jointly captured by the β and δ parameters. The value of δ is the amount the curve is shifted from the ordinate axis, reflecting the moment when discriminative information is first available. The value of (1/β + δ) is the time at which accuracy reaches a common proportion of asymptotic accuracy, namely ($1-e^{-1}$), approximately 63%.

We fit a fully-saturated model to each participants' data by estimating a separate <λ, β, δ> triplet for each of the six Structure × Probe type Target-Distractor condition-pairs. We then used mixed-effects linear regression to test whether either asymptotic performance (λ) or rate of information accrual (1/β + δ) varied by either Structure (Object, Modifier) or Probe Type (Subject, High, Low). While it is conceivable to separately analyze β and δ parameters, practically they trade off during the estimation process. Therefore, the sum (1/β + δ) is more appropriate to analyze in a full-saturated model. We used sum contrasts for the Structure factor. For the Probe type contrasts, we used Helmert contrasts that first compared Subject vs. non-Subject probes, i.e. the average of High and Low conditions parameters, and then High vs. Low non-Subject probes. For purposes of inference, we analyzed over participant parameters. For a convenient visualization, we additionally computed an average d-prime series over all participant data and then fit a fully-saturated model to that series. There was convergence between the two analyses.

Results

In brief, we found that both asymptotic performance and speed were lower for non-Subjects than Subjects. Among the non-Subject attractor positions, we found a Height difference in asymptotic performance only in Object conditions. In Modifier conditions, both attractor positions were equally available in memory. There were no speed of processing differences among probes in the non-Subject positions. Fig 3 visualizes participant parameter estimates and Table 3 summarizes them. Fig 4 visualizes the average SAT curve.

Fig 3. Experiment 2 Participant SAT parameters. Box and scatter plots of individual parameter estimates for the asymptote, λ (d′), rate, β (ms^{-1}), and intercept, δ (ms).

Table 3. Summary of participant parameter estimates in Experiment 2. Mean values are reported in each cell with standard errors in parentheses.

Parameter	Structure	Subject	High	Low
Asymptote λ (d′)	Object	3.2 (.05)	2.9 (.09)	2.7 (.14)
	Modifier	3.2 (.04)	3.1 (.07)	3.1 (.07)
Dynamics 1/β + δ (ms)	Object	1373 (107)	1467 (104)	1495 (128)
	Modifier	1349 (88)	1437 (80)	1477 (109)

Fig 4. Probe discrimination as a function of lag-latency. The visualization of the Lag-latency/d′ series was created by aggregating accuracy data, i.e. first collapsing over subjects, then computing d′. Plot symbols represent empirical d′ values and the smooth lines represent the best-fitting function.

Turning first to asymptotic performance, we found that participants were highly accurate at the task and discriminated between Targets and Distractors with an average d′ of 3.0. There was an overall advantage for Subject probes (t=4.1), which received the highest asymptotic d′ scores. There was also an overall advantage for Modifier structures compared to Object structures (t= 3.3). There was a significant interaction between Subject probes and Structure which nearly leveled the Subject advantage for probes drawn from Modifiers: that is, the NPs inside complex subjects received d′ scores that were almost as high as the Subject probes (although there was still a marginally-significant difference, t=1.84, $p < .10$). There was a significant interaction between Height and Structure (t=3.1), reflecting the fact that probes inside moved objects showed a height effect, with higher asymptotes for higher probes, whereas probes in subject modifiers showed no effect of height.

We then analyzed the combined dynamics of processing. This measure sums the time constant of the fitted curve ($1/\beta$) to its intercept (δ). The resulting value, in milliseconds, has a direct interpretation: it is the time since the onset of the probe at which approximately 63% of asymptotic accuracy is achieved. This value, on average, was 1433 ms. Among our experimental factors, only Subject type affected the combined dynamics: Subject probes led to an advantage of approximately 108 ms (t=3.1) compared to other probes.

Discussion

The special procedure designed to explore memory retrieval of NPs in the sentence, combining probe recognition and SAT, provided us with two sets of findings with regard to the workings of memory for sentences and to the role of memory in attraction. We discuss them in turns.

Three major data points show important differences between memory for units involved in sentences and memory units involved in lists, suggesting that sentence structure plays a key role in regulating accessibility in memory. First, we found that subject heads are more

accessible than any other NP in the sentence. This is true even when the subject was maximally distant from the probe in the linear string, as was the case in sentences with two modifying PPs. Second, we found that the c-commanding object head was more accessible than its modifier, again, despite being linearly further from the probe. These two findings contrast with results from list memorization, where accessibility generally decreases with distance from probe (McElree, 2006). Although it is possible that the c-commanding wh-phrase's advantage could stem from a primacy effect (which manifests in SAT studies in terms of a higher asymptote, but not in terms of faster dynamics, e.g., McElree & Dosher 1989), we do not consider the explanation very likely given the strength of the effect. Third, we found that subject heads are systematically retrieved faster than the other NPs from the sentence, independently of their linear position in the sentence. This finding again shows that the dynamics of word retrieval within the sentence differs from that in word lists, where it is usually the final item in the list that enjoys a retrieval speed advantage. It suggests that storage and retrieval from sentences are driven by constraints from the grammar, and in particular here, the subject status and the c-command/precedence distinction.

The main goal of Experiment 2 was to explore the possible alignment between attraction patterns and memory. As illustrated in Figure 5, the data suggest that this is the case. First, subject heads, with which participants correctly agreed the verb in more than 85% of the cases in the grammaticality judgments of Experiment 1, are more accessible and more quickly accessed than the two attractors. Second, the significantly stronger attraction found for the c-commanding attractor as compared to the preceding one in the object structure in Experiment 1 is reflected in memory accessibility: the former is significantly more accessible than the latter. Third, the lack of difference in terms of attraction between the two attractors in the PP modifier structure aligns with the lack of difference found in terms of their accessibility and their retrieval dynamics. More generally, the three attractors that were found

to trigger the strongest attraction (c-commanding object head in object questions and the two PPs in the modifier structure), triggering about 10% of attraction, show similar accessibility from memory, significantly higher than the weak attractor (the modifier of the object head in object questions), which triggered less than 1% of attraction. In sum, results from Experiment 2 show a close alignment between attraction rates and memory strength.

Fig 5. Comparison between 2 measures of strength. Attraction indexes from Experiment 1 were matched with the D-prime scores from the corresponding condition in Experiment 2. Values were first centered around the grand mean of each experiment to allow for comparison across scales.

General discussion

Many authors have proposed an associative memory plays a key role in attraction, and computational modeling based on ACT-R and related frameworks has shown that such a model captures data (Badecker & Lewis, 2007, Wagers, Lau & Phillips, 2009, Dillon et al. 2013). However, the present study is the first that explicitly measured memory retrieval of the critical NPs of the sentence, and examined the alignment between these measures and attraction. The methods used in the two experiments reported is innovative in two respects: we used jabberwocky materials to reduce semantic influences and ensure that the task taps into structural processes, and we used a direct probe recognition task combined with a speed-accuracy trade-off procedure. Experiment 1 revealed that attraction arises in jabberwocky sentences, and is globally similar in range to that found in natural French sentences (Franck et al., 2006; 2010; 2015): attraction in about 15% of trials with the head of a moved preverbal object and with the highest PP modifier situated within the subject phrase. The first experiment also revealed that attraction in jabberwocky sentences is sensitive to the structural

distinction between c-command and linear intervention, again replicating data collected with similar structures in natural sentences (Franck et al., 2015). Yet, attraction in jabberwocky sentences with double PP modifiers contrasted with findings on the corresponding natural stimuli (Franck et al., 2002) Both modifiers were found to trigger attraction in jabberwocky, although attraction with the lower PP in natural sentences was virtually nonexistent. By specifically probing the various noun phrases of the just-processed sentences, Experiment 2 allowed us to identify differences in their level of accessibility in memory. Two key findings emerged from that experiment. First, memory accessibility closely aligns with attraction patterns: elements that triggered more attraction in Experiment 1 showed higher levels of accessibility in Experiment 2. Subjects, with which agreement is most of the time correctly realized, are retrieved better and faster; c-commanding object heads, which generate more attraction than their modifier, are retrieved better; the two PP modifiers, which generate similar attraction, give rise to similar accessibility in memory. Second, in contrast to reports from word lists experiments, differences in memory parameters (level of accessibility and dynamics) cannot be accounted for by the overall recency of the noun phrase in the sentence: subjects are overall retrieved better and faster than any other noun phrase in the sentence, independently of their linear position in the sentence, and noun phrases situated in a position of c-command to the verb are retrieved better than those situated in a position of precedence to the verb, despite being linearly further from it.

In the remainder of the discussion, we discuss, in turns, our view of the memory architecture that underlies attraction, the special status of subjects, the interplay between semantics and syntax in memory, and task effects in attraction in sentence comprehension.

Hierarchical memory architecture underlying attraction

In the introduction, we reviewed evidence that memory retrieval, for lists and for sentences, is content-addressable. Content-addressability has the major advantage of being

direct and thus fast, but the price to pay is similarity-based interference. Is attraction the consequence of similarity-based interference in sentence processing? Most of the evidence for attraction in sentence comprehension takes the form of a grammatical illusion in ungrammatical sentences: participants read an ungrammatical verb faster if the sentence contains an attractor word that bears the same features than if it does not (Dillon et al., 2013; Lago et al., Tanner et al., 2014; Wagers et al., 2009). As initially proposed by Wagers et al. (2009), this effect can be explained by the involvement of a cue-based retrieval process triggered at the verb by agreement marking: the presence of an attractor matching with the verb gives rise to the erroneous retrieval of that element, satisfying the parser and allowing it to move on faster than if no element matches the verb (see section on Task effects on attraction in sentence comprehension for a discussion of how cue-based retrieval may also be at play in grammatical sentences). Thus, evidence available to-date comes from the finding that the system is fooled by the presence of an element matching the verb's feature, suggesting that this element has been erroneously identified as agreement controller, despite entertaining no syntactic dependency with the verb. Another type of evidence for similarity-based interference in agreement would come from the finding that similarity between the agreement controller and the attractor modulates the strength of attraction. Research on attraction in sentence production, although not couched into this conceptual framework, suggests that morphological, semantic and syntactic similarity may indeed play a key role in attraction (Franck, 2017). Morphological case similarity is probably the most prominent factor that has been identified: indeed, most attraction effects reported throughout the production literature actually arise when the subject and the attractor lack case marking, and are therefore non distinguishable with respect to case, either because the language does not express morphological case on the attractor (English, but also French, Spanish, Italian), or because there is a case syncretism (e.g., Badecker & Kuminiak, 2007; Hartsuiker et al., 2001;

2003; Slioussar, 2018). In contrast, attraction is virtually nonexistent when the head and attractor have distinct morphological case markers (Badecker & Kuminiak, 2007; Lorimor et al., 2008; Malko & Slioussar, 2013; Marusic et al., 2013). With respect to semantic similarity, some studies have shown that attractors with a high overlap of semantic features with the subject head, in terms of animacy or in terms of semantic field (e.g., *The canoe by the sailboats*) trigger more attraction than those with a lower overlap (e.g., *The canoe by the cabins*, Barker et al., 2001; Smith, Franck & Tabor, 2018).

Of particular interest to the present study, studies showing modulations of attraction due to the syntactic position of the attractor may also be taken as evidence of syntactic similarity-based interference. The most striking finding is that an attractor in a c-commanding position with respect to the verb triggers more attraction than those in a mere precedence position. For example, attraction from the accusative object clitic in French *(*Le professeur les lisent*, *The teacher them-ACC read) is stronger than attraction from the dative clitic (**Le professeur leur lit*, *The teacher to them-DAT read, Franck et al., 2010). Similar results were found in Persian speakers (Mirdamadi et al., 2017) who produced significantly more attraction with preverbal accusative objects (e.g., **Parastar chand ta mariz-RA didand*, *The nurse several patients-RA saw-PL) than with preverbal datives (**Parastar be chand ta mariz-RA komak kardand*, *The nurse several patients-RA helped-PL). The same effect was found for sentence-initial objects, with more attraction for accusatives than datives. Whereas the accusative c-commands the verb, the dative is embedded within a (sometimes covert) prepositional layer when it intervenes on the agreement dependency, and thus is only in a position of precedence. Data in French contrasting the dative clitic and the preverbal PP modifier, which also intervenes in terms of precedence, show similar attraction for the two structures (Franck et al., 2010). Along the same lines, attraction from the head of a moved complex object c-commanding the verb is stronger than attraction from the same lexical element when it is in a position of

modifier of the head, in line with what was reported in Experiment 1 here (Franck et al., 2015).

C-commanding the verb is a typical property of subjects; it is therefore tempting to propose that the stronger attraction power of c-commanding positions is an instance of syntactic similarity effect, because c-commanding attractors are, at the syntactic level, more similar to subjects. Yet, c-command differs from morphological case and semantic features in that it lies in a relational property, which is independent of the content of the element itself. The same issue may arise for how to treat the relational property 'being a subject of' (Van Dyke, 2007; Van Dyke & McElree, 2011; Arnett & Wagers, 2017), an issue we return to below. The question is whether there is a reasonably way to accomplish this in a content-addressable memory, short of actually implementing a search algorithm. Kush et al. (2015), who provide evidence that relational information is used to guide retrieval in the processing of bound variable pronouns, consider this issue in great detail. There are two general (search-free) possibilities: either the features used at encoding must be enriched to encode syntactic domains, or c-command can be "spoofed" by properties of activation. Wagers (2008) discusses the possibility that items within the c-command domain of particular heads (like wh-phrases) could have a shared ID or similar context features (cf. Howard & Kahana, 2002b). If this ID is incorporated into the set of retrieval cues, the mechanism responsible to retrieve the agreement controller is expected to be more prone to erroneously retrieve an intervening element carrying that feature, making it more similar to the target. Another possibility is that activation often incidentally tracks syntactic prominence in a way that nearly maps onto c-command (cf. Page & Norris, 1998, for linear order).

Although more work is necessary to specify the mechanisms by which relational information is encoded in memory, our results provide new, direct evidence that memory

representations are shaped by hierarchical structure and key relational constructs (subjecthood and c-command) assumed by syntactic theory.

The special status of subjects

Results from the SAT experiment show that subjects are more accessible and retrieved faster than any other element in the sentence, and that these two parameters are independent of whether the subject is linearly to the probe (as in complex object structures) or farther away (as in double PP structures). This latter finding aligns with McElree & Wagers (2009) who found that subjects separated from the verb by a prepositional phrase modifier (e.g., *The editor of the journal laughed*) are retrieved as quickly as adjacent subjects. In list memorization SAT measures, accessibility is typically found to increase with linear distance to the probe, while retrieval dynamics is identical for all elements, except the last one preceding the probe, being faster (e.g., McElree & Dosher, 1989, but see McElree et al., 2003, and Dillon et al., 2013, for reports of dynamics variations). Our finding, together with that of McElree & Wagers (2009), suggest that subjects remain in focal attention, even if they are separated from their verb, at least when the interpolated materials consist of PP modifiers. Our finding that subject probes led to an advantage of approximately 108 ms closely aligns to estimates made for the focus of attention advantage obtained by McElree, Foraker & Dyer (2003), who used single-response SAT.

In our materials, subjects always did occupy a special position in the linear string: in the Modifier conditions, it occurred at the beginning of the sentence, while in the complex Object conditions, it occurred at the end. And both the beginning and the end of a sequence are privileged positions. Various studies have shown an advantage for the first-mentioned participant in the sentence (e.g., Chang, 1980; Gernsbacher et al., 1988). The first content word in the sentence tends to be read more slowly, all things being equal (Aaronson & Scarborough, 1976), and Gernsbacher suggested that comprehenders use the initial word of

the sentence, which is often the subject, to lay the foundation of their mental model, over which upcoming information will be anchored. However, observations show that the first-mention advantage persists even if the second-mentioned element is also part of the subject (as in *Tina and Lisa argued (...))* and if the first element is not the subject (as in *Because of Tina, Lisa was evicted (...)*) (Gernsbacher & Hargreaves, 1988). Evidence also suggests that sentence comprehension is sensitive to recency effects. When participants hear or read a two-clause sentence, words from the most recent clause are more accessible than those from the earlier clause (e.g., Townsend & Bever, 1978; Caplan, 1972; Chang, 1980; Marslen-Wilson et al., 1978, etc.). However, the timing of the memory task is critical: if the probe is presented together with the last word of the sentence, an advantage is found for the words from the recent clause, but 1400 ms later, an advantage is found for the first-mentioned word, which is arguably reactivated as part of sentence wrap-up processes. Could the faster dynamics and higher accessibility of subjects in our study thus be explained in terms of the primacy and recency effects? While primacy and recency may have contributed to the accessibility of the nouns in our study, recall that we always found a dynamics advantage for the subject head, even when it was not the first word in the sentence. Moreover, previous SAT studies show that the recency advantage shows up in the asymptote, but not in the dynamical parameters (McElree, 2006).

What is it that makes subjects special? One possibility is that the subject function is intimately linked to the construct of 'actor' or 'agent', which is rooted in our ability to understand goal-directed actions: "Agents are a class of objects possessing sets of causal properties that distinguish them from other physical objects (…) as a result of evolution, we have become adapted to track these sets of properties and to efficiently learn to interpret the behavior of these objects in specific ways" (Leslie, 1995, p. 122). Evidence indeed suggests that the human attention system has a special sensitivity to tracking humans and animals,

which are good potential actors (New et al., 2007). The extended Argument Dependency Model (Bornkessel, 2002; Schlesewsky and Bornkessel, 2004) assumes that an actor-based principle guides sentence comprehension, by which the system is primarily designed for seeking to identify the actor, that is, the participant responsible for the state of affairs expressed in the sentence. The linguistic features related to actor identification are: +self (under the view that the first person is the prototypical actor), +animate/human, +definite/specific, +first position, +nominative. Such a model is compatible with content-addressable memory retrieval models, in which actor identification is sensitive to competition from candidates with overlapping features (although it involves specific assumptions about the weighing of the cues, which may vary cross-linguistically, see (Alday, Schlesewsky, & Bornkessel-Schlesewsky, 2014); see Babyonishev & Gibson, 1999). An important property of the model is that interference is 'actor-centered' in that only features of actors are relevant in generating similarity-based interference (Bornkessel-Schlesewsky, 2009). However, our results show that the subjects remain privileged in memory even in the absence of semantics. Arnett & Wagers (2017) argued that subject phrases are directly encoded for their case or syntactic position in the phrase structure tree. Building from the design of Van Dyke & Lewis (2003), they showed that when participants read finite clauses, the only kinds of subjects that could interfere were those that were the subjects of other finite clauses. A variety of other subject properties (e.g., being the agent in an event nominalization: "the marauder's destruction of the village") were ineffective at generating similarity-based interference.

Subjects have many properties that should give them a survival advantage in memory, such as the fact that they often occur first and that they often name the actor participant in an event. But our results show that, even when neither of those properties are relevant, subjects retain their special status in memory. The most plausible remaining explanation, in our view, is that this status derives from their prominent structural position in our stimuli. In our task,

the subject phrase was always the last NP comprehenders encountered that c-commanded the verb. If our sentences had more elaborate complements, it may have been other NPs beside the subject would show a similar advantage. Future research is needed to explore such possibilities.

Finally, our results also suggest that elements from the subject constituent may have a special role to play in attraction, as subject modifiers seemed to be more activated than any of the elements from the object constituent; in fact, their asymptote was nearly as high as that of subjects (although a clear difference remained in their dynamics). Using a two-choice response time paradigm, Staub (2010) found that although response times for correct agreement decisions were similar for structures with subject modifiers and those with moved objects, their underlying distribution was qualitatively different: whereas the effect of a plural subject modifier is due to both a shifting of the distribution to the right and to increased skewing, the effect of a plural object is almost entirely due to skewing. This led him conclude that different mechanisms underlie attraction in these two structures (in line with the early proposal by Bock & Miller, 1991). Although our results also suggest qualitative differences between the two types of elements with respect to their memory status, it is important to keep in mind that both our data and Staub's rely on comparisons across sentences with different structures. Hence, further research is needed to determine whether the difference holds within structures containing both a moved object and PP modifiers, and if so, to better understand whether the difference lies in the sentence processing mechanism underlying these two types of elements, their memory status, or in the linking between memory and processing mechanisms, which remains to be fully fleshed out.

The interplay of semantics and syntax in memory

An important part of the literature on attraction has been concerned with the influence of semantics. Most of the research has focused on the role of the notional representation of the

subject phrase (Eberhard, 1999; Foote & Bock, 2012; (Smith et al., 2018) Vigliocco, Butterworth & Garrett, 1996), and on the influence of semantic correlates of grammatical number and gender features (e.g., Bock, Nicol, & Cutting, 1999 ; Vigliocco & Franck, 2001). A few studies also explored the influence of the semantic relationship between the head and the attractor noun, and showed influences on agreement from the semantic similarity between the subject head and the attractor (Barker et al., 2001) and from the semantic integration between the head and the attractor (Solomon & Pearlmutter, 2004; Gillespie and Pearlmutter, 2011). However, most of the studies on attraction failed to control for these semantic relations within the sentence. The use of jabberwocky materials is a first attempt to explore attraction while controlling it. The comparison between previous results on natural stimuli and the current results on similar structures without semantics provides us with new insights about the role of semantics in attraction.

In line with natural language data on object attraction (Franck et al., 2015), we found that hierarchical height, which coincided with c-command, significantly affected attraction in jabberwocky sentences involving a moved complex object: grammaticality judgments were more penalized (both in terms of accuracy and RTs) when the c-commanding attractor, i.e., the object head, mismatched the subject's number than when the lower attractor, i.e., the object's modifier, mismatched it. Results from the SAT experiment also showed a significant difference in the memory availability of the two nouns, aligning with the attraction profile. This finding suggests that this effect, lying in the structural difference between c-command and precedence, is independent of the semantics. However, a different profile emerged for double PP structures. In contrast to natural language data on sentences with two PP subject modifiers, which showed virtually no attraction from the lower attractor (Franck et al., 2002; Gillespie and Pearlmutter, 2011), no difference was found between the two attractors with jabberwocky sentences: both generated significant attraction, similar to that observed with the

highest PP in natural sentences. Moreover, in line with the attraction profiles, we found that the two nouns were equally available in memory. How can we account for the difference between jabberwocky and natural sentences in that structure?

In the Discussion of Experiment 1, we argued that the difference could not lie in task differences, based on the independent finding that grammaticality judgments on natural language stimuli replicated the stronger attraction effect with the higher PP previously obtained with a sentence completion procedure (Franck & Wagers, 2015). We hypothesized that the lack of a hierarchical distance effect in jabberwocky sentences might be due to the lack of semantic information allowing building a tree in which the second modifier is nested into the first modifier, as is the case in the natural stimuli previously used by Franck et al. (2002). Indeed, if the two modifiers are both attached to the subject head, they are both equidistant to the verb and no distance effect is expected. Nevertheless, results from Gillespie and Pearlmutter (2011) potentially challenge our hypothesis. The authors contrasted sentences similar to Franck et al. (2002) with a nested hierarchical structure, in which the second PP modified the first PP (e.g., "The backpack with the plastic buckles on the leather strap"), to sentences with a flat structure in which both PPs modified the head (e.g., "The highway to the western suburbs with the steel guardrail"). Results showed that the increase of attraction for the highest, first PP was actually independent of whether the second PP is attached to the first PP or to the head: both embedding and flat structures showed stronger attraction with the first PP. In another experiment, the authors manipulated the semantic integration between the PP and the head noun: for example, if one compares the phrases "the book with the torn pages" and "the book by the red pen", the PP *with the torn pages* is more closely integrated to the head *the book* than the PP *by the red pen*. Gillespie and Pearlmutter found stronger attraction from the higher PP than from the lower when the former was highly semantically integrated to the head (e.g., *The book with the torn pages by the red pen* generated more attraction than

The book with the torn page by the red pens), but no difference between the two PPs when the highly integrated PP is the lower PP (e.g., *The book by the red pens with the torn page* generated similar attraction to *The book by the red pens with the torn page*). The authors concluded that attraction rates were determined by a combination of linear distance to the head and semantic integration. They argued that the mechanism underlying the effect of these two factors is sentence planning: when the attractor is linearly closer to the head and/or when it is more integrated semantically to it, it tends to be 'planned' at the same time as the head; in that case, the two nouns are simultaneously active in memory and their numbers therefore have increased chance to interfere. In this so-called 'Scope of planning' account, timing of planning is primarily determined by the linear order in which elements have to be produced: hierarchically higher PPs generate more attraction not in virtue of their hierarchical height but in virtue of their linear closeness to the head. However, semantic integration has the potential to shift the planning (in line with Solomon & Pearlmutter, 2004): elements that are linearly distant but semantically close to the head may still be planned at the same time, and thus have an influence on attraction.

Nevertheless, our new findings on attraction in jabberwocky sentences, in which semantics plays no role and the only factor at play is thus linear proximity, do not support the Scope of planning account. In jabberwocky sentences, the Scope of planning account predicts that linear distance to the head will be the only determinant of attraction, since semantic integration is switched off. Hence, in our double modifier structures, the first PP being closer to the head should generate stronger attraction than the second PP. This is not what we found: linear closeness to the head does not increase attraction. Also, the Scope of planning account predicts that the modifier PP in our complex object structures should trigger more attraction than the object head, because it is linearly closer to the subject head. Again, this is not what

we found: the object head generates more attraction despite being linearly further from the subject head.

In sum, neither specificities of the task, nor distance (hierarchical or linear), nor semantic integration seem to capture the full set of observations on natural and jabberwocky sentences with two PPs. So what is it? Whereas the lack of semantics in jabberwocky sentences modified the attraction effect found for natural sentences with double modifiers, it had no impact on complex objects. Hence, semantics has a different impact on these two structures. The key difference between the two structures is that whereas height is tied to the structural relation of c-command in complex objects, it is looser in the case of PPs. As we already discussed it, double PP sentences can have two different underlying structures: an embedded structure or a flat structure. But even single PP sentences may have different underlying structures, as subject modifiers have the option of being arguments or adjuncts (Schütze & Gibson, 1999). Although these factors may not play a significant role in attraction per se (Solomon & Pearlmutter, 2004), we suggest that the unconstrained syntactic structure of the double PP structure is responsible for maintaining the two PPs in a similar memory state, and thus give them a similar attraction potential. We propose that semantics would play a key role in constraining syntactic structure building and thus providing a stable representation to story in memory when structural constraints are undetermined. In the absence of semantics, double PP sentences remain 'floating' without finding a clear memory anchor, giving rise to similar attraction from the two PPs, in contrast to natural sentences. In contrast, for complex objects, there is no other alternative parse tree: the object is necessarily an argument of the verb, and the first NP is necessarily the head of that complex constituent. Semantics is unnecessary for building the underlying hierarchical structure, which would be why similar, structure-based results are found for both jabberwocky and natural sentences.

Conclusion

This study presents two new tools providing new avenues for the study of the relations between sentence processing and memory: the use of jabberwocky materials allowed us for maximally controlling the role of semantics and lexical frequency, and thus focus on the specificities of syntactic processing, while the transposition of the probe recognition task to sentences with a Speed-Accuracy Trade-off design allowed us exploring the structure of memory representations underlying sentences. The data show that attraction arises independently of semantics, under the guidance of structural principles, similar to attraction in natural sentences. More critically, the data provide direct evidence for the role of memory as a key factor in agreement and attraction, in that more accessible elements in memory generate more attraction. It suggests a tight link between theoretical constructs from syntactic theory, in particular those of subject and c-command, and memory representations, and with this, reopens the hypothesis that the theory of competence is also a theory of performance.

Acknowledgements

The research was funded by the Fonds National Suisse de la Recherche (International Short Visit) to J. Franck. We wish to thank Brian McElree, Whit Tabor and Julie Van Dyke, for enriching discussions on this work. Nevertheless, we take complete responsibility for the content of the paper.

References

Aaronson D, Scarborough HS. Performance theories for sentence coding: Some quantitative evidence. Journal of Experimental Psychology: Human Perception and Performance. 1976; 2:56–70.

Alday PM, Schlesewsky M, Bornkessel-Schlesewsky I. Towards a computational model of actor-based language comprehension. Neuroinformatics. 2014; 12(1): 143-179.

Arnett N, Wagers M. Subject encodings and retrieval interference. Journal of Memory and Language. 2017; 93: 22-54. dio: 10.1016/j.jml.2016.07.005

Babyonishev M, Gibson E. The complexity of nested structures in Japanese. Language. 1999; 75: 423-450.

Badecker W, Kuminiak F. Morphology, agreement and working memory retrieval in sentence production: Evidence from gender and case in Slovak. Journal of Memory and Language. 2007; 56(1): 65-85.

Barker J, Nicol JL, Garrett MF. Semantic factors in the production of number agreement. Journal of Psycholinguistic Research. 2001; 30:91–114.

Bates D, Maechler M, Bolker B, Walker S, Christensen RHB, Singmann H, Grothendieck G. Package "lme4". R package version. 2014; 1:1-10.

Bock K, Miller CA. Broken agreement. Cognitive psychology. 1991; 23(1): 45-93.

Bock K, Cutting JC. Regulating mental energy: Performance units in language production. Journal of memory and language. 1992; 31(1): 99-127.

Bock JK, Nicol J, Cutting JC. The ties that bind: Creating number agreement in speech. Journal of Memory and Language. 1999; 40: 330-346.

Bock K, Eberhard KM, Cutting JC, Meyer AS, Schriefers H. Some attractions of verb agreement. Cognitive Psychology. 2001; 43(2): 83-128.

Bornkessel I. The Argument Dependency Model: A Neurocognitive Approach to Incremental Interpretation. PhD dissertation. Max Planck Institute of Cognitive Neuroscience; 2001.

Bornkessel I, Schlesewsky M. The Role of Prominence Information in the Real-Time Comprehension of Transitive Constructions: A Cross-Linguistic Approach. Language and Linguistics Compass. 2009; 3(1):19-58.

Caplan D. Clause boundaries and recognition latencies for words in sentences. Perception & Psychophysics. 1972; 12:73–76.

Chomsky N. Minimalist inquiries: The framework. In Martin R, Michaels D, Uriagereka J, editors. Step by step—Essays in Minimalist syntax in honor of Howard Lasnik. Cambridge, MA: MIT Press. 2000. pp. 89–155.

Chang FR. Active memory processes in visual sentence comprehension: Clause effects and pronominal reference. Memory & Cognition. 1980; 8:58–64.

Clark SE, Gronlund SD. Global matching models of recognition memory: How the models match the data. Psychonomic Bulletin and Review. 1996; 3(1): 37-60.

Clifton C, Frazier L, Deevy P. Feature manipulation in sentence comprehension: 2703. Italian journal of linguistics. 1999; 11(1):11-40.

Cowan N. The magical number 4 in short-term memory: a reconsideration of mental storage capacity. Current Directions in Psychological Science. 2001; 19(1):51-57

Dillon B, Chow WY, Wagers M, Guo T, Liu F, Phillips C. The structure-sensitivity of memory access: evidence from Mandarin Chinese. Frontiers in psychology. 2013; 5: 10-25.

Eberhard KM. The accessibility of conceptual number to the processes of subject- verb agreement in English. Journal of Memory and Language. 1999; 41(4): 560-578.

Eberhard KM, Cutting JC, Bock K. Making Syntax of Sense: Number Agreement in Sentence Production. Psychol Rev. 2005; 112(3): 531-559. doi: 10.1037/0033-295x.112.3.531

Fedorenko E, Gibson E, Rohde D. The nature of working memory capacity in sentence comprehension: Evidence against domain-specific working memory resources. Journal of Memory and Language. 2006; 54(4): 541-553.

Ferreira F. The misinterpretation of noncanonical sentences. Cognitive Psychology. 2003; 47(2): 164-203. doi: 10.1016/s0010-0285(03)00005-7

Foote M, Bock K. The role of morphology in subject–verb number agreement: A comparison of Mexican and Dominican Spanish. Language and cognitive processes. 2012; 27(3): 429-461.

Franck J, Vigliocco G, Nicol J. Attraction in sentence production: The role of syntactic structure. Language and Cognitive Processes. 2002; 17(4): 371-404.

Franck J, Lassi G, Frauenfelder UH, Rizzi, L. Agreement and movement: A syntactic analysis of attraction. Cognition. 2006; 101(1): 173-216.

Franck J, Soare G, Frauenfelder UH, Rizzi, L. Object interference in subject–verb agreement: The role of intermediate traces of movement. Journal of Memory and Language. 2010; 62(2): 166-182.

Franck J. Syntactic Encoding: Novel Insights Into the Relationship Between Grammar and Processing. In Fernandez E, Cairns H , editors. The handbook of psycholinguistics. Wiley :NJ. 2017.

Franck J, Wagers M. Hierarchical structure and memory retrieval mechanisms in attraction: An SAT study. Poster presented at the CUNY conference on sentence processing, Los Angeles, March 19-21, 2015.

Gernsbacher MA, Hargreaves DJ, Bee-Man ME. Accessing sentence participants: Evidence for clausal processing; Paper presented at the annual meeting of the Psychonomic Society; Chicago, IL. 1988.

Gillespie M, Pearlmutter NJ. Against Structural Constraints in Subject-Verb Agreement Production. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2011; 39(2): 515-528. doi: 10.1037/a0029005

Gordon PC, Hendrick R, Johnson M. Memory interference during language processing. Journal of Experimental Psychology-Learning Memory and Cognition. 2001; 27(6): 1411-1423. doi: 10.1037//0278-7393.27.6.1411

Gordon PC, Hendrick R, Johnson M. Effects of noun phrase type on sentence complexity. Journal of Memory and Language. 2004; 51(1): 97-114. doi: 10.1016/j.jml.2004.02.003

Gronlund SD, Edwards MB, Ohrt DD. Comparison of the retrieval of item versus spatial position information. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1977; 23:1261–1274.

Hartsuiker RJ, Antón-Méndez I, Van Zee M. Object attraction in subject-verb agreement construction. Journal of Memory and Language. 2001; 45: 546-572.

Häussler J, Bader M. Agreement checking and number attraction in sentence comprehension: Insights from German relative clauses. Travaux du cercle linguistique de Prague. 2009.

Häussler J, Bader M, Bayer J. Number attraction in sentence comprehension. Paper presented at the Poster Presented at the 9th Annual Conference on Architecture and Mechanisms for Language Processing. 2003.

Howard MW, Kahana MJ. When does semantic similarity help episodic retrieval? Journal of Memory and Language. 2002b; 46: 85–98.

Hupet M, Fayol M, Schelstraete MA. Effects of semantic variables on the subject—verb agreement processes in writing. British Journal of Psychology. 1998; 89(1): 59-75.

Jäger L, Engelmann F, Vasishth S. Similarity-based interference in sentence comprehension: Literature review and Bayesian meta-analysis. Journal of Memory and Language. 2017; 94: 316-339.

Jonides J, Lewis RL, Nee DE, Lustig CA, Berman MG, Moore KS. The mind and brain of short-term memory. Annual Review of Psychology. 2008; 59:193-224.

Kimball J. Aissen J. I think, you think, he think. Linguistic inquiry. 1971; 2: 241–246

King J, Just MA. Individual differences in syntactic processing: The role of working memory. Journal of Memory and Language. 1991; 30: 580–602.

Kush D, Lidz J, Phillips C. Relation-sensitive retrieval: Evidence from bound variable pronouns. Journal of memory and language. 2015; 82: 18–40.

Kuznetsova A, Brockhoff PB, Christensen RHB. Package 'lmerTest'. R package version. 2016.

Lago S, Shalom D, Sigman M, Lau E, Phillips C. Agreement attraction in Spanish comprehension. Journal of Memory and Language. 2015; 82: 133–149. doi: 10.1016/j.jml.2015.02.002

Leslie AM. A theory of agency. In D. Sperber, D. Premack, A. J. Premack, editors. Symposia of the Fyssen Foundation. Causal cognition: A multidisciplinary debate. New York, NY, US: Clarendon Press/Oxford University Press. 1995. pp. 121-149.

Lewis RL. Interference in short-term memory: The magical number two (or three) in sentence processing. Journal of Psycholinguistic Research. 1996. 25(1): 93-115.

Lewis RL, Vasishth S. An Activation-Based Model of Sentence Processing as Skilled Memory Retrieval. Cognitive Science. 2005; 29(3): 375-419. doi: 10.1207/s15516709cog0000_25

Lewis RL, Vasishth S, Van Dyke JA. Computational principles of working memory in sentence comprehension. Trends in cognitive sciences. 2006; 10(10): 447-454.

Lorimor H, Bock K, Zalkind E, Sheyman A, Beard R. Agreement and attraction in Russian. Language and Cognitive Processes. 2008; 23(6): 769–799.

MacDonald MC, Pearlmutter NJ, Seidenberg MS. The lexical nature of syntactic ambiguity resolution. Psychol Rev. 1994; 101(4): 676.

Macmillan NA, Creelman CD. Detection theory: A user's guide. Cambridge, England: Cambridge University Press. 1991.

Malko A, Slioussar N. Attraction errors in gender agreement: Evidence from Russian. In: S. Franks et al. editors. Formal Approaches to Slavic Linguistics: The Third Indiana Meeting, MI: Michigan University Press. 2013. pp. 162-175.

Martin AE, McElree B. Direct-access retrieval during sentence comprehension: Evidence from Sluicing. Journal of memory and language. 2008; 64(4): 327–343. doi: 10.1016/j.jml.2010.12.006

Martin AE, McElree B. Memory operations that support language comprehension: evidence from verb-phrase ellipsis. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2009; 35(5): 1231.

Marslen-Wilson W, Tyler LK, Seidenberg M. Sentence processing and the clause boundary. In: Levelt WJM, Flores d'Arcais GB, editors. Studies in the perception of language. London: Wiley. 1978. pp. 219–246.

Marušič F, Nevins A, Badecker B. The grammars of conjunction agreement in Slovenian. Syntax. 2013; 18(1): 39-77. doi.org/10.1111/synt.12025

McElree B. Accessing short-term memory with semantic and phonological information: A time-course analysis. Memory and Cognition. 1996; 24: 173–187.

McElree B. Attended and non-attended states in working memory: Accessing categorized structures. Journal of Memory and Language. 1998; 38: 225–252.

McElree B. Sentence comprehension is mediated by content-addressable memory structures. Journal of psycholinguistic research. 2000; 29(2): 111-123.

McElree B. Working memory and focal attention. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2001; 27(3): 817-835.

McElree B. Accessing recent events. In Ross BH, editor. The psychology of learning and motivation San Diego, Academic Press, 2006.

McElree B, Dosher BA. Serial Position and Set Size in Short-Term Memory: The Time Course of Recognition. Journal of Experimental Psychology: General. 1989; 4: 346-373.

McElree B, Foraker S, Dyer L. Memory structures that subserve sentence comprehension. Journal of Memory and Language. 2003; 48(1): 67-91.

Mirdamadi F, Kahnemuyipour A, Franck J. Object attraction and the role of structural hierarchy: Evidence from Persian. Poster presented at AMLaP, Lancaster (UK), 2017.

Mulligan NW. Word frequency and memory: Effects on absolute versus relative order memory and on item memory versus order memory. Memory & Cognition. 2001; 29(7): 977-985.

Nairne JS. The myth of the encoding-retrieval match. Memory. 2002; 10(5-6): 389-395.

New J, Cosmides L, Tooby J. Category-specific attention for animals reflects ancestral priorities, not expertise. Proceedings of the National Academy of Sciences USA. 2007; 104:16598–603.

Oberauer K. Interference between storage and processing in working memory: Feature overwriting, not similarity-based competition. Memory and Cognition. 2009; 37(3): 346-357.

Öztekin I, McElree B. Proactive interference slows recognition by eliminating fast assessments of familiarity. Journal of Memory and Language. 2007; 57(1): 126-149.

Page MPA, Norris D. The primacy model: A new model of immediate serial recall. Psychological Review. 1998; 105(4): 761-781.

Parker D, Shvartsman M, Van Dyke JA. The cue-based retrieval theory of sentence comprehension: New findings and new challenges. Language processing and disorders. Newcastle: Cambridge Scholars Publishing. 2017.

Potter MC. Rapid serial visual presentation (RSVP): a method for studying language processing. In Kieras D, Just M, editors. New Methods in Reading Comprehension Research. Hillsdale, NJ: Erlbaum. 1984. pp. 91–118.

Quirk R, Greenbaum S, Geoffrey L, Svartvik J. A Grammar of Contemporary English. London: Longman 1972.

Reinhart T. The syntactic domain of anaphora. PhD dissertation. MIT, Cambridge, MA 1976.

Santesteban M, Pickering MJ, Branigan HP. The effects of word order on subject–verb and object–verb agreement: Evidence from Basque. Journal of Memory and Language. 2013; 68(2): 160-179.

Schlesewsky M, Bornkessel I. On incremental interpretation: Degrees of meaning accessed during sentence comprehension. Lingua. 2014; 114(9):1213-1234. doi: 10.1016/j.lingua.2003.07.006

Schütze CT, Gibson E. Argumenthood and English prepositional phrase attachment. Journal of Memory and Language. 1999; 40(3): 409-431.

Slioussar N. Forms and features: The role of syncretism in number agreement attraction. Journal of Memory and Language. 2018; 101: 51-63.

Smith G, Franck J, Tabor W. A Self- Organizing Approach to Subject–Verb Number Agreement. Cognitive Science. 2018; 42 (S4):1043-1074. doi: 10.1111/cogs.12591

Solomon ES, Pearlmutter NJ. Semantic integration and syntactic planning in language production. Cognitive psychology. 2004; 49(1): 1-46.

Staub A. On the interpretation of the number attraction effect: Response time evidence. Journal of Memory and Language. 2009; 60: 308-327.

Staub A. Response time distributional evidence for distinct varieties of number attraction. Cognition. 2010; 114(3): 447-454. doi: 10.1016/j.cognition.2009.11.003

Stolz WS. A study of the ability to decode grammatically novel sentences. Journal of Verbal Learning and Verbal Behavior. 1967; 6: 867-873. doi.org/10.1016/S0022-5371(67)80151-8

Tabor W, Hutchins S. Evidence for self-organized sentence processing: Digging-in effects. Journal of Experimental Psychology-Learning Memory and Cognition. 2004; 30(2): 431-449.

Tanner D, Nicol J, Brehm L. The time-course of feature interference in agreement comprehension: Multiple mechanisms and asymmetrical attraction. Journal of memory and language. 2014; 76: 195-215.

Thornton R, MacDonald MC. Plausibility and grammatical agreement. Journal of Memory and Language. 2003; 48(4): 740-759.

Townsend D J, Bever TG. Interclause relations and clausal processing. Journal of Verbal Learning and Verbal Behavior. 1978; 17(5): 509-521.

Tucker MA, Wagers MW. Agreement attraction in infinitival complements. UCSC LRC Laboratory Report. 2010; 23-43.

Van Dyke JA, Lewis RL. Distinguishing effects of structure and decay on attachment and repair: A cue-based parsing account of recovery from misanalyzed ambiguities. Journal of Memory and Language. 2003; 49(3): 285-316.

Van Dyke JA. Interference effects from grammatically unavailable constituents during sentence processing. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2007; 33(2): 407.

Van Dyke JA, McElree B. Retrieval interference in sentence comprehension. Journal of Memory and Language. 2006; 55(2): 157-166.

Van Dyke JA, McElree B. Cue-dependent interference in comprehension. Journal of memory and language. 2011; 65(3): 247-263.

Vigliocco G, Franck J. When sex affects syntax: Context effects in sentence production. Journal of Memory and Language. 2001; 45: 368-390.

Vigliocco G, Hartsuiker RJ, Jarema G, Kolk HHJ. How many labels on the bottles? Notional concord in Dutch and French. Language and Cognitive Processes. 1996; 11: 407-421.

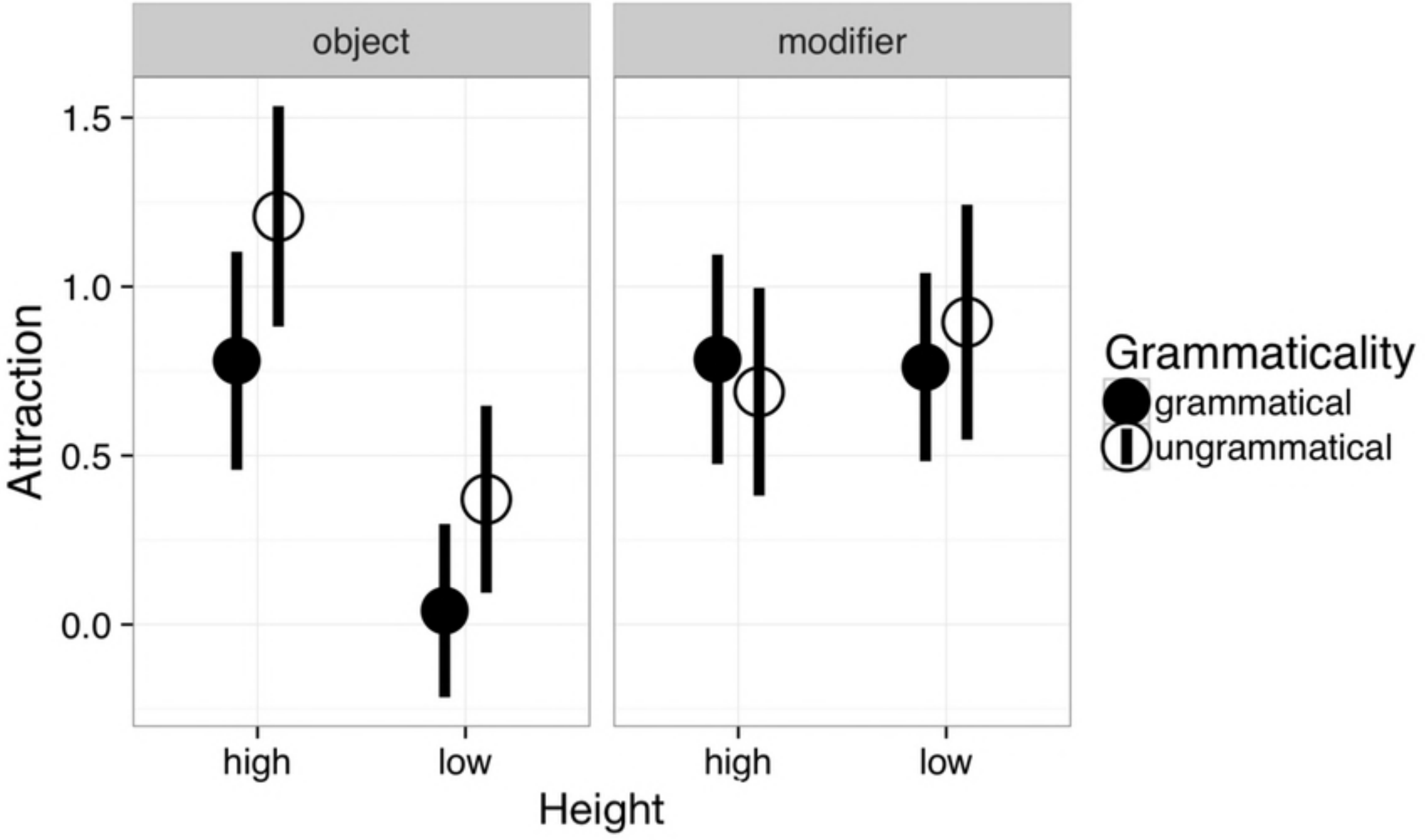
Villata S, Tabor W, Franck J. Encoding and retrieval interference in sentence comprehension: Evidence from agreement. Frontiers in Psychology. 2018; 9:2.

Wagers MW, Lau EF, Phillips C. Agreement attraction in comprehension: Representations and processes. Journal of Memory and Language. 2009; 61(2): 206-237. doi: 10.1016/j.jml.2009.04.002

Wagers M, McElree B. Working memory and language processing: theory, data and directions for future research. In Boeckx C, Grohmann K, editors. The Cambridge Handbook for Biolinguistics. Cambridge, UK: Cambridge University Press, 2013.

Wickelgren WA. Network strength theory of storage and retrieval dynamics. Psychological Review. 1976; 83(6): 466-478.

Wickelgren WA, Corbett AT, Dosher BA. Priming and retrieval from short-term memory: A speed accuracy trade-off analysis. Journal of Verbal Learning and Verbal Behavior. 1980; 19: 387–404.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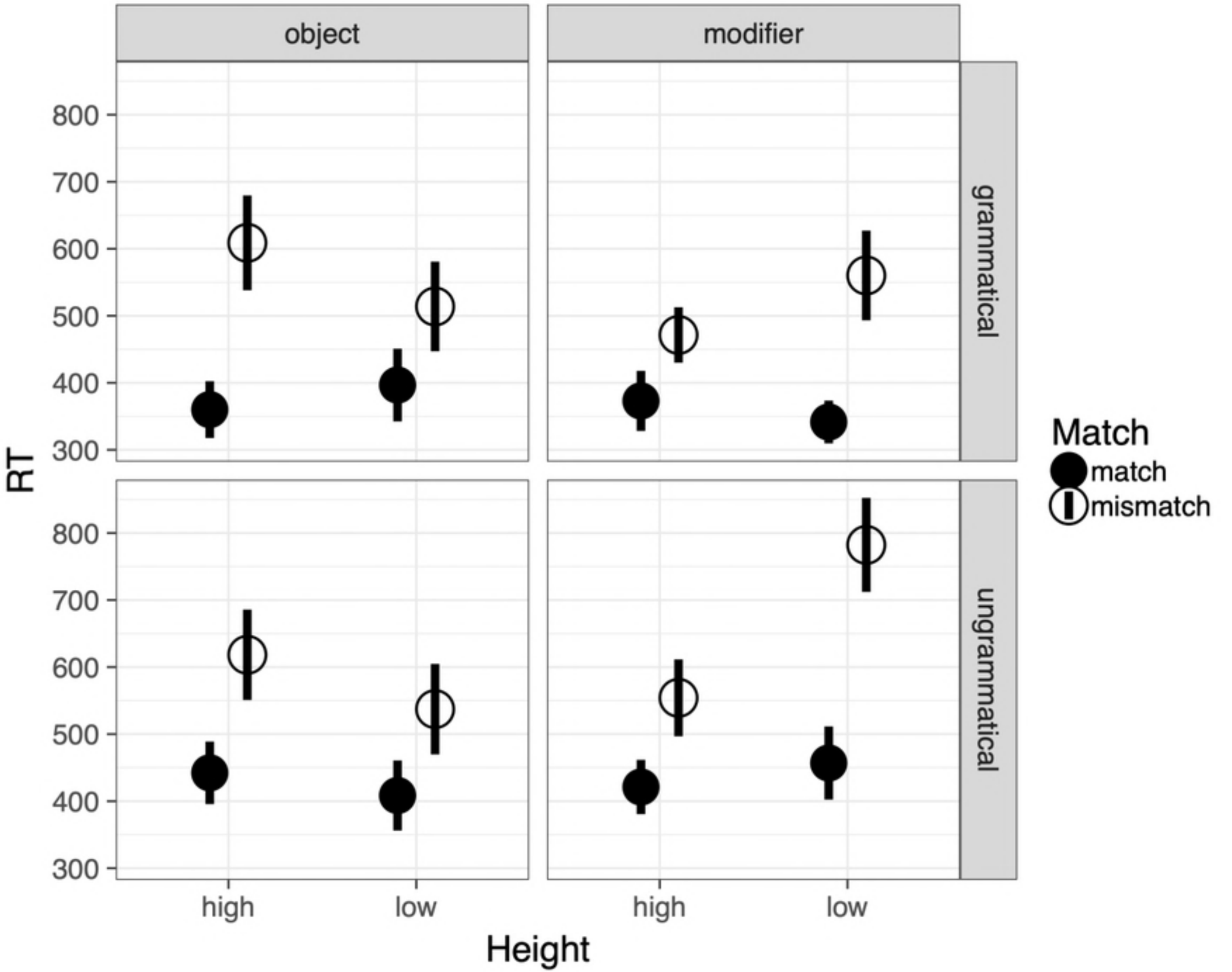
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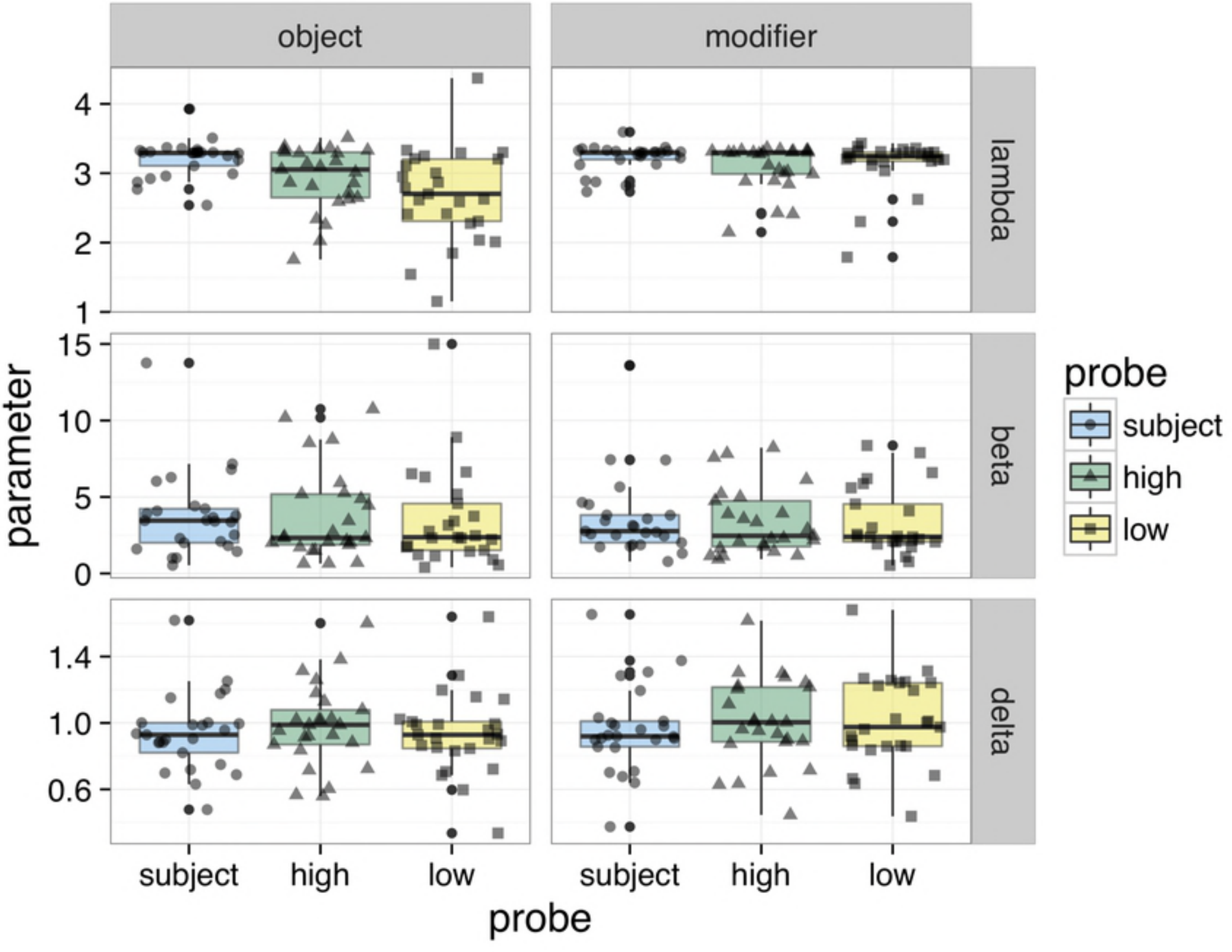
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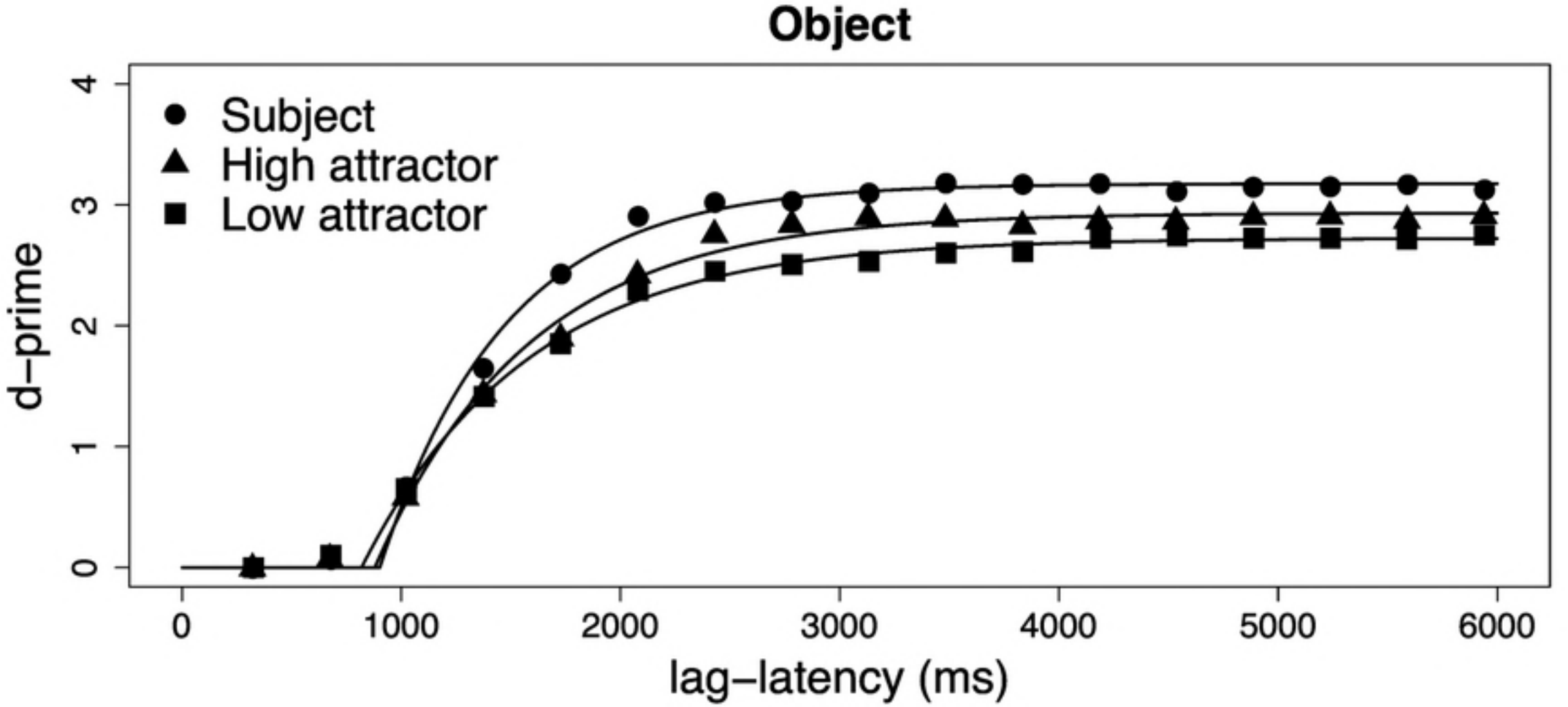

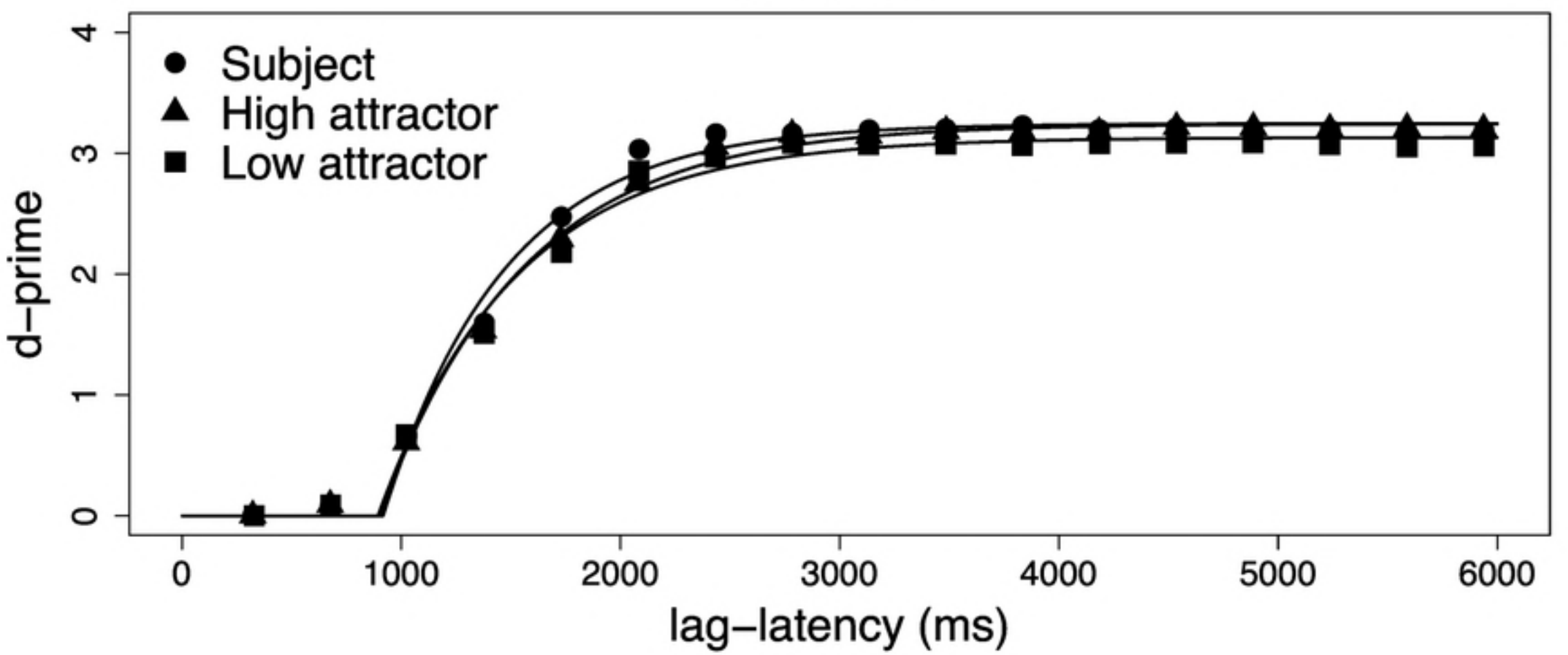

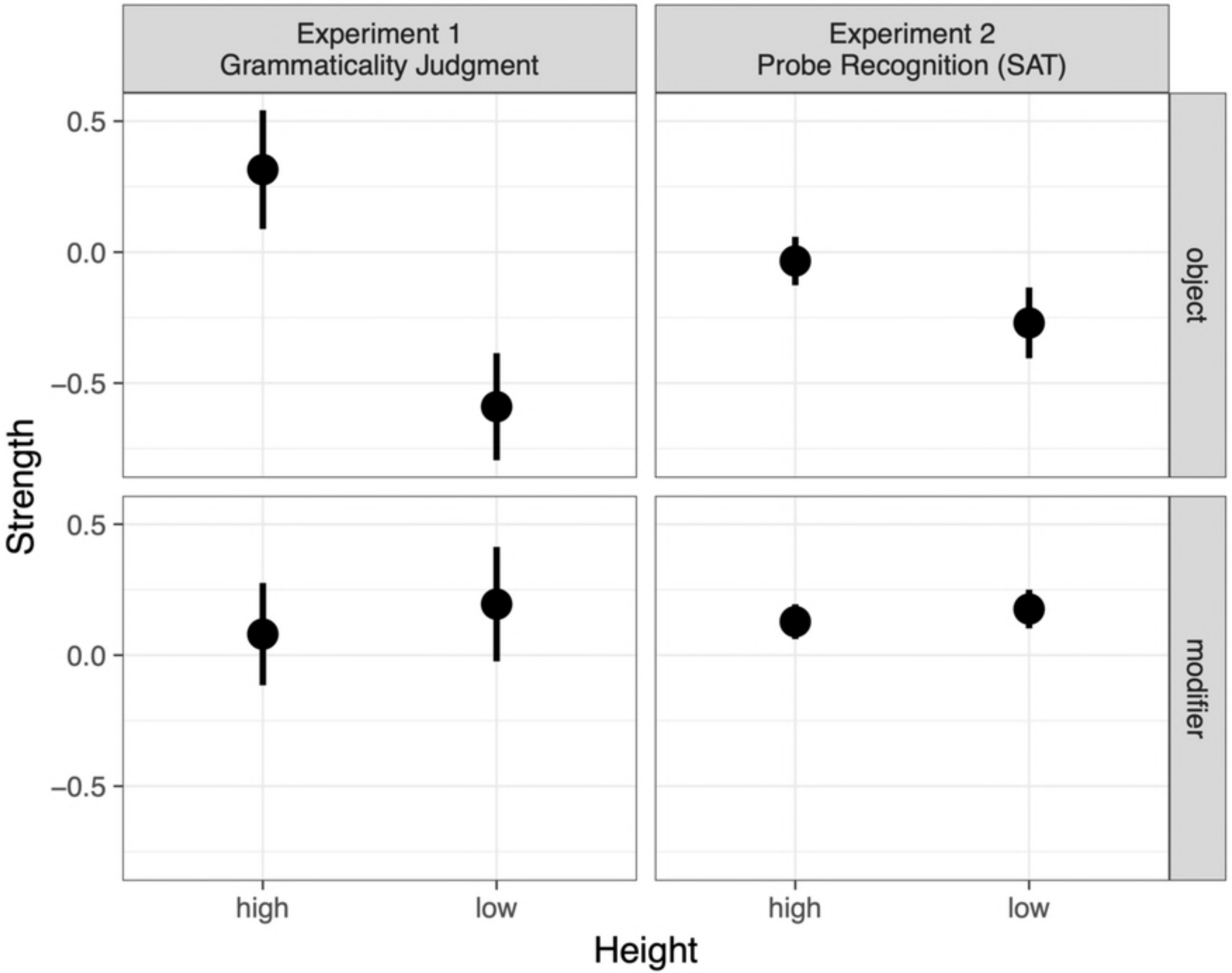
Experiment 1
Grammaticality Judgment
Experiment 2
Probe Recognition (SAT)
object
modifier
Strength
0.5
0.0
−0.5
high
low
Height