ARGUMENT-HEAD DISTANCE AND PROCESSING COMPLEXITY: EXPLAINING BOTH LOCALITY AND ANTILOCALITY EFFECTS

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Although proximity between arguments and verbs (locality) is a relatively robust determinant of sentence-processing difficulty (Hawkins 1998, 2001, Gibson 2000), increasing argument-verb distance can also facilitate processing (Konieczny 2000). We present two self-paced reading (SPR) experiments involving Hindi that provide further evidence of antilocality, and a third SPR experiment which suggests that similarity-based interference can attenuate this distance-based facilitation. A unified explanation of interference, locality, and antilocality effects is proposed via an independently motivated theory of activation decay and retrieval interference (Anderson et al. 2004).*

1. INTRODUCTION. Although constraints on working memory have long been assumed to affect sentence processing (Miller & Chomsky 1963, Frazier 1979), over the years the connection between sentence-processing research and cognitive psychologists' views of working memory has become increasingly opaque. We suggest in this article that instead of defining the resource limitations of working memory in terms of linguistically defined primitives (for example, the number of new discourse referents introduced (Gibson 1998, 2000) or the number of words per constituent (Hawkins 1998, 2001, 2004)), a more direct approach would be to utilize theoretical primitives developed within working-memory research in cognitive psychology (see, for example, Miyake & Shah 1999). Our purpose here is to show that this approach is completely consistent with the basic insights furnished by linguistically centered theories, but has the advantage of providing a more explanatory answer to the question: why are certain constructions harder to process than others?

We focus on the claim in human sentence processing that parsing difficulty is partly a function of the distance between an argument and a verb (head): the greater the distance, the greater the difficulty in integrating the argument with the verb. One theory that instantiates this idea is Gibson's (2000) DEPENDENCY LOCALITY THEORY (hereafter, DLT).[1] In DLT, argument-head distance is quantified by the number of new discourse

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[1] Another major locality theory is Hawkins's EARLY IMMEDIATE CONSTITUENTS or EIC (Hawkins 2001), but it is not completely clear to us whether EIC is a diachronic explanation of typological variation, or an explanation of both typological variation and moment-by-moment real-time sentence processing. If the latter, EIC's locality claims face essentially the same issues as those of DLT, as discussed below (cf. Konieczny 2000, Christianson 2002, and Vasishth 2003).

referents intervening, where a discourse referent is defined as 'an entity that has a spatiotemporal location so that it can later be referred to with an anaphoric expression, such as a pronoun for NPs or tense on a verb for events' (Gibson 2000:103). Thus, both noun phrases and verbs can introduce new discourse referents. As an example, consider the subject and object relative clause sentences in 1 (Grodner & Gibson 2005).

(1) a. The reporter [who sent the photographer to the editor] hoped for a good story.
b. The reporter [who the photographer sent to the editor] hoped for a good story.

According to DLT, increased processing difficulty should occur at *sent* in the object relative 1b compared to the same verb in the subject relative 1a. This is because in 1b the newly introduced discourse referent *photographer* intervenes between the argument *reporter* and the head *sent.* This relatively simple complexity metric is extremely powerful in its ability to account for a variety of behavioral data from a range of languages (Gibson 1998, 2000, Babyonyshev & Gibson 1999, Nakatani et al. 2000, Hsiao & Gibson 2003).

There are, however, counterexamples to such locality effects. For example, Konieczny (2000) showed in a German self-paced reading study that the verb *hingelegt* was read faster (was easier to process) in 2a than in 2b.

(2) a. Er hat das Buch, [das Lisa gestern gekauft hatte], hingelegt.
he has the book that Lisa yesterday bought had laid.down
'He has laid down the book that Lisa had bought yesterday.'
b. Er hat das Buch hingelegt, [das Lisa gestern gekauft hatte].
he has the book laid.down that Lisa yesterday bought had
'He has laid down the book that Lisa had bought yesterday.'

Konieczny's work demonstrated that interposing elements between argument and heads in verb-final constructions can facilitate processing. Since real-time human sentence processing is in general incremental and predictive (see, for example, Tyler & Marslen-Wilson 1977, Konieczny 1996, Scheepers et al. 1999, Steedman 2000), it is plausible to assume that the interposed material somehow allows an easier anticipation of the upcoming verb (the exact mechanism is discussed in §5). Konieczny refers to this as the ANTICIPATION HYPOTHESIS.

In this article, we present two Hindi experiments which provide further evidence for facilitation in verb-final structures. We propose an explanation for facilitation and other effects in terms of very general assumptions about human cognition: activation decay of items is argued to result in locality effects, and reactivation in anticipatory facilitation. In addition, a third experiment suggests that processing difficulty due to increased similarity can be explained in terms of a decrease in activation due to the presence of multiple possible candidates during an integration event (such as integrating arguments and a verb).

Apart from being independently motivated, this activation-based explanation has the important property that instead of viewing working memory as a limited-capacity system with a discrete upper bound, one can align sentence-processing difficulty directly with the view in cognitive psychology that the apparently limited capacity of working memory emerges from very general (and often conflicting) constraints (Miyake & Shah 1999).

We turn next to the experimental evidence from Hindi that relates to the various locality-based theories mentioned above.[2]

2. EXPERIMENT 1. Our first experiment considered the effect of interposing material between two arguments of a verb in a center-embedding construction. Consider the double center-embedding shown in 3. This is a control construction (Bickel & Yadava 2000) with the syntactic structure shown in Figure 1.[3]

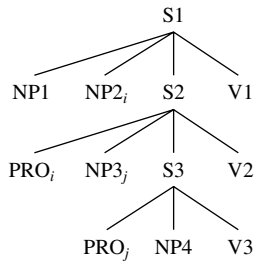

FIGURE 1. Schematic representation of the double center-embedding in 3.

(3) Sita-ne Hari-ko Ravi-ko kitaab-ko khariid-neko bol-neko kahaa.
Sita-ERG Hari-DAT Ravi-DAT book-ACC buy-INF tell-INF told
'Sita told Hari to tell Ravi to buy the book.'

In this construction, consider the situation at the innermost verb (V3) *khariid-neko* 'buy-INF': this is a transitive verb and takes NP3 (*Ravi-ko* 'Ravi-DAT') and NP4 (*kitaab-ko* 'book-ACC') as arguments.[4] Consequently, when this verb is processed, these two previously encountered arguments must be integrated with the lexically specified information about the verb's argument structure in order for the meaning of the sentence to be comprehended. As mentioned above, DLT predicts that the effort required to integrate NP3 and NP4 with V3 should increase if new discourse referents intervene between the arguments and the verb: the cost of building a discourse referent is assumed to be cognitively expensive in that it consumes limited memory resources (Gibson 2000, Grodner & Gibson 2005). For example, if an adjunct introducing new discourse referents were to intervene between NP4 and V3, this would increase argument-head distance (Figure 2).

The prediction of the anticipation hypothesis depends on how exactly it is characterized. One possibility is time-driven facilitation: the interposed material could facilitate processing because the arguments of the upcoming (not yet seen) verb are being integrated into a structure being built incrementally, and this integration process could

[2] Hindi or Hindi-Urdu is an Indo-Aryan language spoken primarily in South Asia. Word order is canonically (most frequently) subject-object-verb, but can be varied considerably depending on discourse context (Gambhir 1981, Mahajan 1990, Kidwai 2000). It is a split-ergative language and noun phrases generally have overt morphological suffixes marking case, but bare NPs do appear in certain contexts. Finite verbs typically agree with bare-argument nouns in number, person, and gender, subject to certain constraints that are not relevant here (McGregor 1995).

[3] There is debate in the literature about whether the embedded infinitival clause in such structures is nominal (Davison 1991, Butt 1993) or verbal (Mohanan 1994, Bickel & Yadava 2000), but this issue is orthogonal to the present discussion since the predictions of the various models do not hinge upon the major category of the infinitival.

[4] The case-marker *-ko* can mark dative or accusative case.

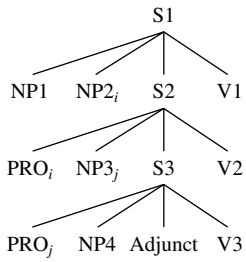

FIGURE 2. Schematic representation of double center-embedding with an adjunct intervening between V3 and its arguments.

include building a prediction of a verb with a particular subcategorization frame. It is possible that the interposed material merely furnishes sufficient time for the integration and prediction process. This is Konieczny's claim (2000:644):

> When arguments of a clause-final verb are being integrated into the structure, the type of the verb [whether it is transitive, etc.] is further constrained to allow only certain arguments to come. When the verb arrives, everything is already in place and there is no need to retrieve an argument from any place far away. Constraining the verb type amounts to type-deduction, which might go beyond valency prediction, if enough time is provided. [A relative clause] preceding the verb might just provide enough time to finish type-deduction as far as possible.

In §5 we discuss evidence suggesting that time-driven facilitation cannot be correct and present an alternative explanation.

DLT and the anticipation hypothesis make the following predictions for double center-embeddings like 3. In a comparison of example 4b with the baseline condition in 4a (repeated from 3, where nothing intervenes between NP4 *kitaab-ko* 'book-ACC' and V3 *khariid-neko* 'buy-INF'), DLT predicts that the presence of the adverbial phrase *jitnii jaldii ho sake* 'as soon as possible' in 4b should have no effect on processing difficulty at the verb, since the adverb does not introduce any discourse referents.[5] In 4c and 4d, by contrast, DLT predicts a slowdown at the verb because each of the intervening phrases (a postpositional phrase or PP, and a relative clause or RC, respectively) contains one new discourse referent (*dukaan* 'shop' and *mez* 'table', respectively).[6] The anticipation hypothesis, by contrast, predicts that in each of the conditions 4b,c,d there should be a facilitation at the innermost verb because the intervening material furnishes more time for predicting the verb type.

[5] As associate editor Shari Speer points out, an adverb may in principle introduce a discourse referent since there are cases where one adverb can refer to an earlier adverb. For example, one could plausibly argue that *as soon as possible* could be referred to by an adverb like *then* at some later point in a discourse. Perhaps a more nuanced characterization of discourse referents should be adopted in the context of DLT; however, as we show here, the notion of processing cost in terms of the number of new intervening discourse referents is itself problematic (cf. Warren 2001, Knoeferle et al. 2005, Warren & Gibson 2005).

[6] As a referee has pointed out, it has been argued that caseless NPs in Hindi, including those appearing with postpositions as in this experiment, may be nouns incorporated with the following verb (Mohanan 1995; cf. Wescoat 2002); it could therefore be argued that such caseless NPs do not introduce new discourse referents. But under the definition of discourse referents in DLT mentioned earlier (Gibson 2000:103), they must be regarded as discourse referents since they can be referred to later on in discourse. It certainly is possible that this definition of discourse referents does not apply in Hindi; if so, DLT would predict no slowdowns at all in any condition. But under no construal of the discourse status of the NP would DLT predict a speedup.

(4) a. Nothing intervening
Sita-ne Hari-ko Ravi-ko kitaab-ko khariid-neko bol-neko kahaa.
Sita-ERG Hari-DAT Ravi-DAT book-ACC buy-INF tell-INF told
'Sita told Hari to tell Ravi to buy the book.'

b. Adverb intervening
Sita-ne Hari-ko Ravi-ko kitaab-ko **jitnii.jaldii.ho.sake**
Sita-ERG Hari-DAT Ravi-DAT book-ACC as.soon.as.possible
khariid-neko bol-neko kahaa.
buy-INF tell-INF told
'Sita told Hari to tell Ravi to buy the book as soon as possible.'

c. Prepositional phrase (PP) intervening
Sita-ne Hari-ko Ravi-ko kitaab-ko **ek baṛhiya dukaan-se**
Sita-ERG Hari-DAT Ravi-DAT book-ACC a good shop-from
khariid-neko bol-neko kahaa.
buy-INF tell-INF told
'Sita told Hari to tell Ravi to buy the book from a good shop.'

d. Relative clause (RC) intervening
Sita-ne Hari-ko Ravi-ko kitaab-ko **jo mez-par thii**
Sita-ERG Hari-DAT Ravi-DAT book-ACC that table-on was
khariid-neko bol-neko kahaa.
buy-INF tell-INF told
'Sita told Hari to tell Ravi to buy the book that was lying on a/the table.'

A previous study (Vasishth 2003) compared center-embedding types with no intervening element (4a) and those with an intervening adverb (4b) in order to determine if a facilitation occurred in Hindi. Consistent with the anticipation hypothesis, but not with locality-based theories, a speedup was observed at the verb occurring immediately after the intervening adverb. However, evidence for anticipation would be far more compelling if the results can be replicated with a range of experimental manipulations. This is the motivation for the two experiments presented next.

2.1. METHOD, MATERIALS, AND SUBJECTS. All experiments presented in this article employed the noncumulative self-paced moving-window method (Just et al. 1982). The subjects' task was to press the space bar in order to view each successive phrase; each time the space bar was pressed, the previous phrase would disappear and the next phrase would appear. Reading time (in milliseconds) was taken as a measure of relative momentary processing difficulty. A yes/no comprehension question was presented after each sentence; this was meant to ensure that subjects were attending to the sentences. Subjects with less than 70% correct responses were not included in the data analysis; typically this resulted in the exclusion of the data from four or five subjects in each experiment.

The phrase segmentation of the stimuli was done according to the white spaces between words/phrases shown in 4, with the exception that the interposed phrases in boldface were presented as a single segment. The period (which in Hindi is a vertical line) was presented as a separate final segment, making it the wrap-up region.[7] The

[7] Reading times are usually elevated at the end of the sentence; see, for example, Mitchell & Green 1978: 627 for discussion.

separation was not unnatural because written/printed text has a small amount of blank space between the final letter of a word and the period.

Since experiment 1 had four conditions, quadruples of twenty-four stimuli sentences were created, and these were assigned to four groups (twenty-four sentences in each group) in a counterbalanced manner (Ray 2000). The stimuli sentences in each group were pseudo-randomly interspersed with fifty-two fillers or distractors, twenty-four of which were stimuli from another, unrelated experiment. The stimuli for all experiments presented here are given in the appendix in abbreviated form. The complete set of stimuli and distractors is available from the first author upon request.

The subjects were undergraduate and graduate students recruited in January 2003 at Jawaharlal Nehru University, New Delhi. Each subject was paid the Indian-rupee equivalent of two US dollars. At the beginning of each experiment the task was explained to subjects, and eight practice sentences were presented before the start of the actual experiment.

2.2. RESULTS AND DISCUSSION. The reading-time data are summarized in Figure 3. All three planned comparisons between the baseline condition (4a) and the other three conditions showed a significant facilitation at the innermost verb when material intervened. In the adverb-interposed condition (4b) the by-subjects ANOVA's results were $F1(1,43) = 15.06$, $p = 0.0004$, and the by-items ANOVA's were $F2(1,23) = 6.37$, $p = 0.02$; in the PP-interposed condition (4c), $F1(1,43) = 16.20$, $p = 0.0002$; $F2(1,23) = 8.1$, $p = 0.01$; and in the RC-interposed condition (4d), $F1(1,43) = 11.11$, $p = 0.0019$; $F2(1,23) = 7.03$, $p = 0.02$. As the confidence intervals in the figure show, reading time at the second verb was also significantly faster in the intervention condi-

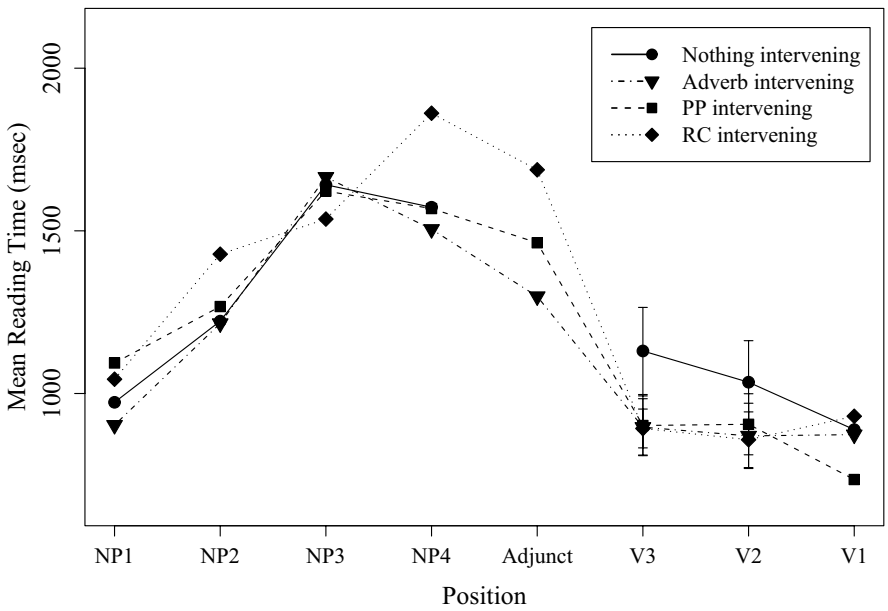

FIGURE 3. Overall results of experiment 1; 95% confidence intervals.

tions; we return presently to a more precise characterization of the effects at the second verb.[8]

As a referee pointed out to us, it is important to eliminate the possibility that spillover from the preceding region is the source of the observed facilitation at the verb.[9] Since the preverbal regions were not identical in the nothing-intervening versus intervening conditions, the amount of spillover from the preverbal region onto the verb could significantly differ in the contrasting conditions, and may indeed be the underlying explanation for effects observed at the verb.

Spillover can be taken into account systematically by factoring it out in the statistical model. One commonly used approach in psycholinguistics for factoring out potentially confounding factors is the use of residuals. In the present context that would mean a regression (for each subject) of the reading time at position $n + 1$ against its immediately preceding region n. Then, for each subject a set of residual scores can be calculated by subtracting the subject's regression-equation estimates from the observed scores, with an ANOVA carried out on the residuals. This approach is standardly used in psycholinguistics to factor out the effect of word length on a word's reading time (Ferreira & Clifton 1986). However, in the present situation, linear mixed-effects models (equivalently, multilevel or hierarchical linear models) provide a better and more informative approach (Pinheiro & Bates 2000).

This regression method allows spillover from the preceding region to be taken into account directly as a fixed effect (with separate intercepts for each subject) as well as a random effect (with separate slopes fit for each subject), in addition to the fixed effect of the experimental manipulation. The other random effects in the model are of course the subjects and items.[10]

For example, in a treatment comparison with j levels of Locality, the statistical model with only main effects has the following form, where i ranges over subjects.[11]

$$(5)\quad y_{ij} = \mu + b_i + \beta_1 \text{Locality}_{ij} + (\beta_2 + \zeta_i)\text{Spillover}_i + \epsilon_{ij}$$

Here, the random effect of Spillover is expressed by two variables: b_i is a random intercept fit for each subject, and ζ_i is a random slope.

Although the linear mixed-effects model (LME) is a well-known and widely used technique in statistical data analysis, its use is not standard in psycholinguistics, perhaps for historical reasons (Baayen 2004). It is therefore appropriate to include a few words

[8] The fourth NP in the RC-interposed condition was significantly slower than the other NPs. Although we have no theoretically motivated explanation for this, one possibility is that the subjects could see that the next segment (the RC) would be relatively long, and this may have led to a preparatory slowdown. Only targeted replications could determine if this slowdown is robustly present.

[9] Mitchell explains the phenomenon of spillover as follows:

> In most immediate processing tasks the end of one response measure is immediately followed by the beginning of another, together with a new portion of text. In this situation any uncompleted processing will spill over from one response measure to the next. In others words, certain aspects of processing will be postponed and join a queue or buffer so that they can be dealt with later. . . . Here, the response measure will be influenced not only by the problems in the current display but also by any backlog or processing that may have built up in the buffer. (Mitchell 1984:76)

[10] In keeping with the convention in psycholinguistics, we fit separate models for by-subject and by-items effects, but we note here that with the linear mixed-effects model both random effects can and should be specified within a single model (Baayen 2004).

[11] For a more detailed and technical presentation, see Pinheiro & Bates 2000, Raudenbush & Bryk 2002.

motivating this modeling approach. LME has certain inherent advantages (Pinheiro & Bates 2000), the most important being: (i) higher power in treatment comparisons, (ii) freedom from assumptions about constant variance (homoscedasticity) and constant covariance (compound symmetry), (iii) constant variance of difference scores (sphericity), (iv) more flexible modeling of diverse sources of heterogeneity and correlation, and (v) the ability to model unbalanced and incomplete repeated-measures data.

In addition, LME has demonstrated effectiveness in analyzing the immediate issue at hand. Psycholinguistic experiments involving covariates such as spillover, frequency, and word length have been used in several cases to separate out the theoretically important empirical phenomena from nuisance variables (Suckow et al. 2006).

In the present experiment, the subjects (and items) are the random effects (the experimental conditions being nested within these), and the experimental conditions and spillover are the fixed effects. The effect of spillover was taken into account using both the commonly used residuals technique and the alternative approach suggested here, linear mixed-effects models.

In the residuals approach a linear model was computed for each subject using all the $\langle n, n + 1 \rangle$ word pairs in order to maximize the data available. The planned pairwise comparisons were recomputed on the residuals, and the results are summarized in Figure 4. Reading time at the critical, innermost verb remains faster in the intervention conditions than in the baseline. Residual reading time at the verb in the adverb-interposed condition (4b) is significantly faster than in the baseline condition (4a; $F1(1,43) = 7.24$, $p = 0.01$; $F2(1,23) = 4.63$, $p = 0.045$). The same holds for the PP-interposed condition (4c; $F1(1,43) = 10.33$, $p = 0.0026$; $F2(1,23) = 7.03$, $p = 0.016$) and the RC-interposed condition (4d; $F1(1,43) = 12.54$, $p = 0.001$; $F2(1,23) = 8.10$, $p = 0.01$).

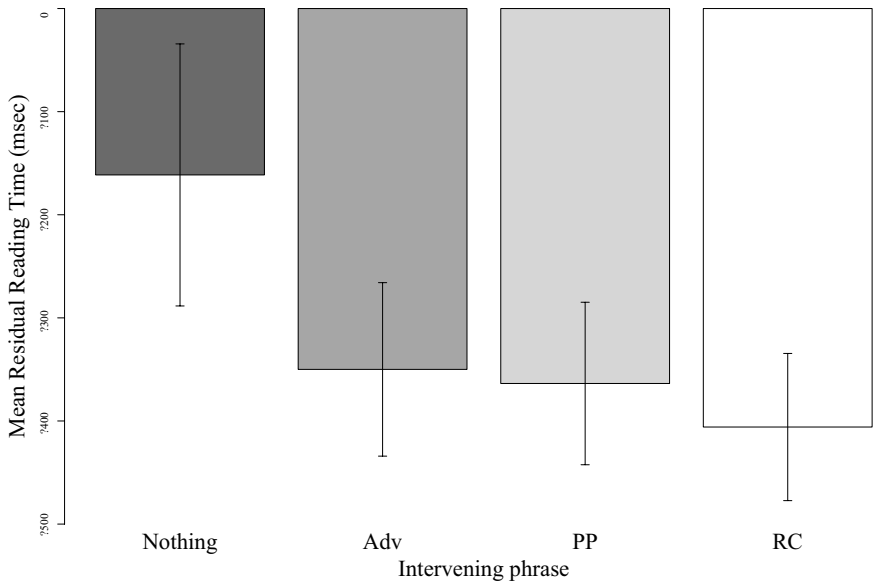

FIGURE 4. Residual reading times in experiment 1 at the innermost verb; 95% confidence intervals.

We turn next to the results of the linear mixed-effects model. We report (for the innermost and second verbs) the effect of intervention, controlling for the effect of the

preceding region, and the interaction between the two main effects. The second verb's ANOVAs are also of interest here because the spillover effect there reflects the impact of the innermost verb's processing continuing into the second-verb region. Table 1 gives a summary of the linear mixed-effects model analysis.

INTERVENING PHRASE	INTERVENTION EFFECT	SPILLOVER EFFECT	INTERACTION
Adverb	√ √	√ √	× ×
PP	√ √	√ √	× √
RC	√ √	√ √	× ×

TABLE 1. Summary of linear mixed-effects model analysis at the innermost verb in experiment 1. The checkmark indicates a significant effect, and the × indicates nonsignificance. Each cell has two marks, the first for the by-subjects analysis and the second for by-items. Any *p*-value greater than 0.05 is considered to be nonsignificant. 'Intervention effect' refers to the effect of interpolated material on the verb, 'spillover effect' to the effect of processing carried over from the region preceding the critical one, and 'interaction' to these two factors' interaction.

At the innermost verb the adverb-interposed condition was significantly faster ($F1(1,43) = 9.8$, $p = 0.003$; $F2(1,22) = 7.1$, $p = 0.014$), and there was a significant spillover effect ($F1(1,416) = 11.4$, $p = 0.0008$; $F2(1,458) = 16.8$, $p < 0.0001$). No interaction was found (Fs < 1). In the PP-interposed condition, there was a main effect of intervention ($F1(1,43) = 9.43$, $p = 0.0037$; $F2(1,22) = 5.6$, $p = 0.03$) and of spillover ($F1(1,416) = 38.4$, $p < 0.0001$; $F2(1,458) = 52$, $p < 0.0001$), and a significant by-items interaction ($F1(1,416) = 2.9025$, $p = 0.09$; $F2(1,458) = 4.3$, $p = 0.04$). In the RC-interposed condition, there was a main effect of intervention ($F1(1,43) = 11.50$, $p = 0.002$; $F2(1,22) = 7.40$, $p = 0.01$), a main effect of spillover ($F1(1,416) = 24.80$, $p < 0.0001$; $F2(1,458) = 34.61$, $p < 0.0001$), and no interaction (Fs < 1).

INTERPOSED ITEM	INTERVENTION EFFECT	SPILLOVER EFFECT	INTERACTION
Adverb	√ ×	√ √	√ √
PP	× ×	√ √	× ×
RC	√ √	√ √	√ √

TABLE 2. Summary of linear mixed-effects model analysis at the second verb in experiment 1. See Table 1 for explanation of marks and column headings.

At the second verb, the results were as follows (see Table 2 for a summary). In the adverb-interposed condition there was a main effect of intervention in the by-subject analysis ($F1(1,43) = 4.62$, $p = 0.04$; $F2(1,22) = 3.18$, $p = 0.09$) and of spillover ($F1(1,416) = 35.11$, $p < 0.0001$; $F2(1,458) = 41.73$, $p < 0.0001$), and an intervention-spillover interaction ($F1(1,416) = 11.10$, $p = 0.001$; $F1(1,458) = 13.9$, $p = 0.0002$). In the PP-interposed condition there was a marginal main effect of intervention in the by-subjects ANOVA ($F1(1,43) = 3.52445$, $p = 0.07$; $F2(1,22) = 1.32$, $p = 0.26$), a main effect of spillover ($F1(1,416) = 15.72$, $p = 0.0001$; $F2(1,458) = 29.73$, $p < 0.0001$), and a marginal interaction in the by-items ANOVA ($F1(1,416) = 1.26$, $p = 0.26$; $F2(1,458) = 3.40$, $p = 0.07$). Finally, in the RC-interposed case there was a main effect of intervention ($F1(1,43) = 6.31$, $p = 0.016$; $F2(1,22) = 4.38$, $p = 0.05$), a main effect of spillover ($F1(1,416) = 25.06$, $p < 0.0001$; $F2(1,458) = 31.07$, $p < 0.0001$), and an interaction ($F1(1,416) = 15.53$, $p = 0.0001$; $F2(1,458) = 15.94$, $p = 0.0001$).

In summary, the mixed-effects model analysis at the innermost verb shows that processing is significantly faster when an adverb, PP, or RC precedes it, even after the effect of the preceding region is factored out. The significant effect of spillover suggests that the preceding region's processing did indeed continue into the critical region. At

the second verb, the intervention and spillover effects remain unchanged, and in addition there are significant interactions between the intervention and spillover effects.

Experiment 1 thus extends the results in Konieczny 2000 and Vasishth 2003 and provides further evidence that is challenging for locality-based theories. There is, however, one concern. Double center-embeddings were used as stimuli, and although these structures are in principle grammatical, subjects report that these are fairly difficult to process, probably because at least four NPs must be maintained in memory before any verb is seen. It is possible that the results obtained in experiment 1 reflected special processing strategies adopted by subjects for such unusual sentences. In order to address this issue, a second experiment was conducted using constructions that are intuitively easier to process.

3. EXPERIMENT 2. The baseline conditions in experiment 2 were object and subject relatives, illustrated in 6a,b. Here, the first verb encountered (in this example, *dekhaa* 'saw') takes the first and second NPs as arguments. Distance between arguments and verb can be increased by interposing a phrase like *mez-ke piiche gire.hue* 'fallen behind a/the table', which has the following properties: (i) it introduces two new discourse referents (*mez* 'table' and the tense on the verb *gire.hue* 'fallen'), (ii) the verb takes as argument the direct object of the corresponding baseline sentence (here, *kaagaz* 'paper'; see 6c,d), and (iii) the adjunct modifies the main verb (*dekhaa* 'saw' in the examples below).

(6) a. Object relative, no intervening discourse referents
Vo kaagaz jisko us laṛke-ne dekhaa bahut puraanaa thaa.
that paper which that boy-ERG saw very old was
'That paper which that boy saw was very old.'

b. Subject relative, no intervening discourse referents
Vo laṛkaa jisne us kaagaz-ko dekhaa bahut jigyaasu thaa.
that boy who that paper-ACC saw very inquisitive was
'That boy who saw that (piece of) paper was very inquisitive.'

c. Object relative, two intervening discourse referents
Vo kaagaz jisko us laṛke-ne **mez-ke piiche gire.hue** dekhaa
that paper which that boy-ERG table-GEN behind fallen saw
bahut puraanaa thaa.
very old was
'That paper which that boy saw fallen behind a/the table was very old.'

d. Subject relative, two intervening discourse referents
Vo laṛkaa jisne us kaagaz-ko **mez-ke piiche gire.hue** dekhaa
that boy who that paper-ACC table-GEN behind fallen saw
bahut jigyaasu thaa.
very inquisitive was
'That boy who saw that (piece of) paper fallen behind a/the table was very inquisitive.'

Schematic views of the structures are shown in Figures 5 and 6, which correspond to 6a,b and 6c,d respectively. Figure 6 shows an example of a structure where material intervenes between the verb V2, and NP1 and NP2. In this example, the intervening material consists of a sentential adjunct containing an NP3, a postposition that forms a PP with NP3, and a verb that takes as adjunct the resulting PP and as argument (as its subject) the direct object in the baseline-condition sentences (i.e. NP1 in object relatives, and NP2 in subject relatives).

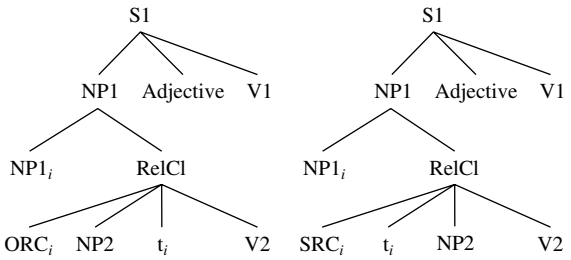

FIGURE 5. Schematic representation of object and subject relative clauses.

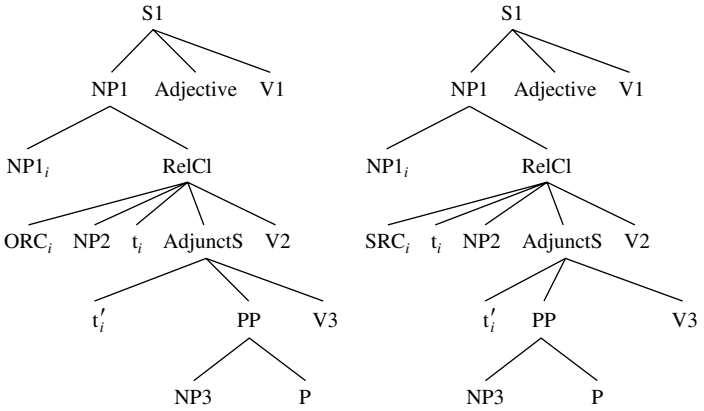

FIGURE 6. Schematic representation of object and subject relative clauses with a sentential adjunct intervening between V2 and its arguments NP1 and NP2.

As in experiment 1, DLT predicts a longer reading time at V2 when the intervening discourse referents are present (compared to the respective baseline conditions), whereas the anticipation hypothesis predicts easier processing at V2 when argument-head distance is increased. These predictions were tested using the self-paced reading task.

3.1. RESULTS AND DISCUSSION. The first contrast examined was the effect of increasing argument-head distance in object relatives (6a,c). As shown in Figure 7, increased argument-head distance resulted in a significantly shorter reading time at the second verb, V2 (only in the by-subjects analysis: $F1(1,54) = 6.36$, $p = 0.02$; $F2(1,23) = 4.86$, $p = 0.04$). The second contrast of interest was the effect of increased argument-head distance in subject relatives (6b,d). As shown in Figure 8, here, too, increasing distance resulted in a significantly shorter reading time at V2 ($F1(1,54) = 13.85$, $p = 0.0005$; $F2(1,23) = 7.53$, $p = 0.013$). No group effects were found in any of the contrast analyses.

Experiment 2 thus provides further evidence problematic for locality-based theories but consistent with the anticipation hypothesis. As in experiment 1, it is possible that the speedup at the verb is attributable to the preceding region. A residual analysis was therefore carried out, and the results were weaker but substantially unchanged. In object relatives the reading time at the critical region, the main verb, was marginally faster in the intervening condition compared to the baseline ($F1(1,54) = 3.80$, $p = 0.06$;

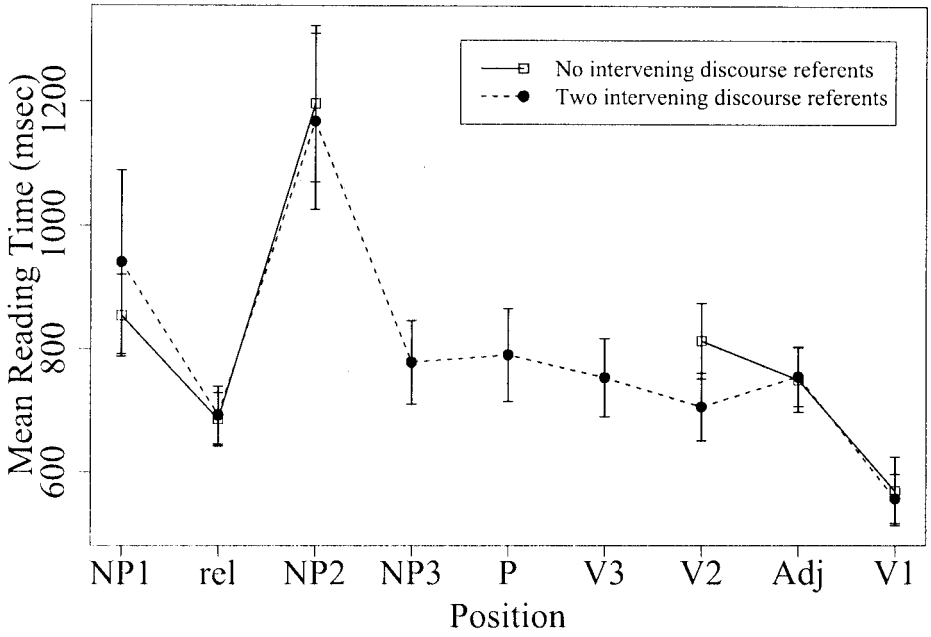

FIGURE 7. Phrase-by-phrase reading times in experiment 2, object relatives; 95% confidence intervals.

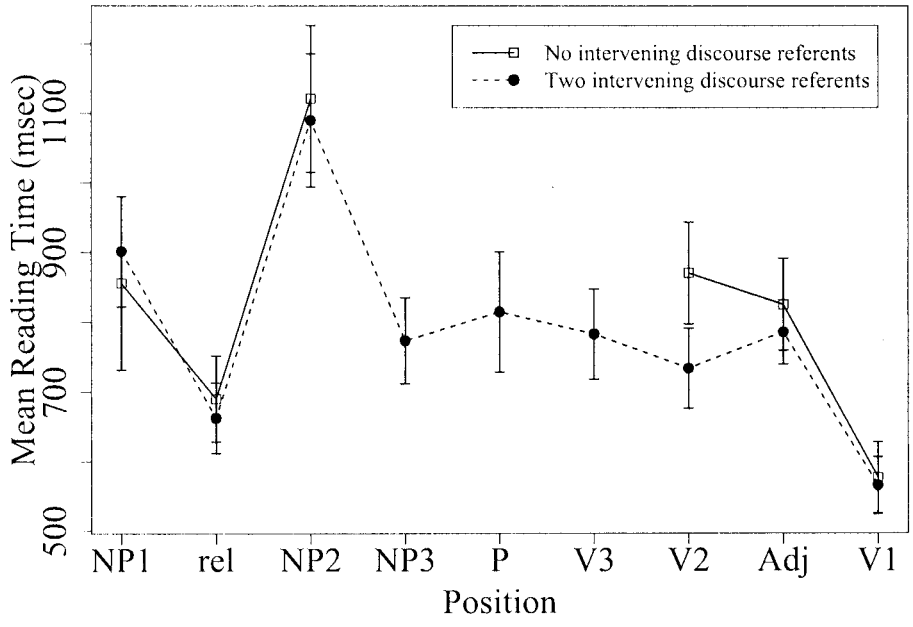

FIGURE 8. Phrase-by-phrase reading times in experiment 2, subject relatives; 95% confidence intervals.

F2(1,23) = 3.54, $p = 0.08$). A significant speedup was found in subject relatives (*F1*(1,54) = 10.18, $p = 0.002$; *F2*(1,23) = 5.90, $p = 0.03$). Analyses based on the linear mixed-effects model are presented next.

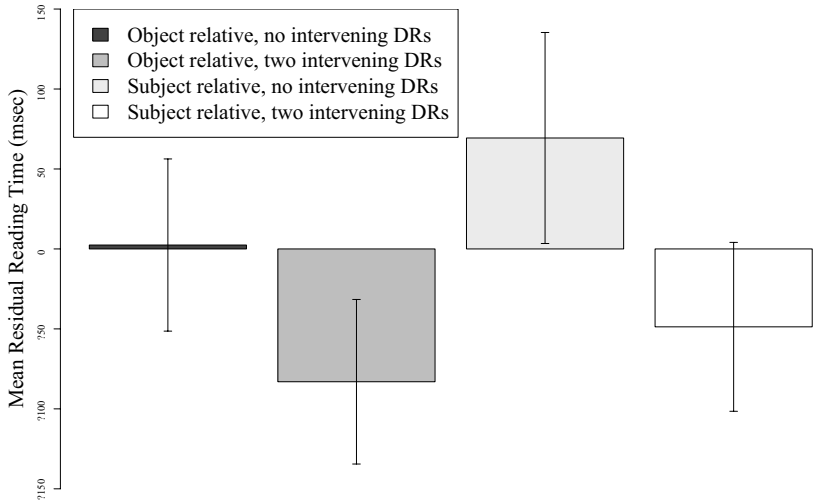

FIGURE 9. Residual reading times in experiment 2 at main verb; 95% confidence intervals.

INTERPOSED ITEM	INTERVENTION EFFECT	SPILLOVER EFFECT	INTERACTION
Object relatives	√ √	√ √	× ×
Subject relatives	√ √	√ √	× ×

TABLE 3. Summary of linear mixed-effects model analysis at the second verb in experiment 2. See Table 1 for explanation of marks and column headings.

As summarized in Table 3, at the embedded verb in object relatives there was a main effect of intervention (*F1*(1,54) = 6.62, $p = 0.01$; *F2*(1,23) = 6.63, $p = 0.02$) and a main effect of spillover (*F1*(1,48) = 49.88, $p < 0.0001$; *F2*(1,610) = 83.65, $p < 0.0001$), but no interaction was found (*F1* < 1; *F2*(1,610) = 1.32, $p = 0.26$). In subject relatives there was a main effect of intervention (*F1*(1,54) = 9.5165, $p = 0.003$; *F2*(1,23) = 8.44, $p = 0.008$) and of spillover (*F1*(1,548) = 24.42, $p < 0.0001$; *F2*(1,610) = 46.02, $p < 0.0001$), but no interaction (*F1* < 1; *F2*(1,610) = 1.02, $p = 0.3$).

4. EXPLAINING THE INTERVENTION EFFECT. Grodner and Gibson (2005:285) suggest a plausible explanation for the speedup observed here and in the earlier experiments on German (Konieczny 2000) and Hindi (Vasishth 2003): 'it is possible that modifiers that are dependents of the predicted head to constrain its semantic and syntactic attributes. This might permit the processor to preactivate those features and facilitate integration.' Under this view, the anticipation effect due to adverbs and PPs (experiment 1) is explained by intervening items preactivating the verb prediction.

As for modifiers like relative clauses that are not dependents of the predicted head, Grodner and Gibson (ibid.) suggest that 'intervening constitutents can make a verb easier to interpret without being dependent on that verb. For instance, the sentence in

[7b] is more plausible than that in [7a], because the subject modifier provides a basis for the verbal event.'

(7) a. The fisherman cried.
b. The fisherman who was cutting onions cried.

As discussed at the beginning of this article, locality-based effects have often been observed, at least in English. Grodner and Gibson demonstrate such effects in their experiment 2. Here, RCs and PPs were inserted between arguments and verbs in the same manner as in the Hindi experiments, but in addition they 'specifically controlled for plausibility, so that adding a modifier did not increase (or decrease) the plausibility of the resultant NP-verb integration' (Grodner & Gibson 2005:285). Thus, their expectation was that locality effects would show up in this experiment, and indeed there were clear effects.

However, recent work suggests that when the preceding region is controlled for so as to reduce or eliminate spillover, antilocality effects are seen even in English (Jaeger et al. 2005). Jaeger and colleagues carried out a self-paced reading study in which the intervening region had one, two, or three PPs. They found that reading times at the verb *bought* were faster with increasing number of intervening PPs—an antilocality effect.

(8) a. The player [that the coach met at 8 o'clock] bought the house . . .
b. The player [that the coach met by the river at 8 o'clock] bought the house . . .
c. The player [that the coach met near the gym by the river at 8 o'clock] bought the house . . .

Thus, it is possible that spillover is responsible for the locality effects observed in experiments like Grodner and Gibson's experiment 2. Note, however, that this does not entail that locality effects do not occur at all. We believe that these will robustly be found if we manipulate distance indirectly. An example is a self-paced study by Van Dyke and Lewis (2003). As shown in 9 below, in this experiment one factor was ambiguity (presence/absence of the sentential complement *that*), and another was distance between an argument (here, the noun *student*) and verb (*was standing*).

(9) a. The assistant forgot that the student **was standing** in the hallway.
b. The assistant forgot the student **was standing** in the hallway.
c. The assistant forgot that the student who knew that the exam was important **was standing** in the hallway.
d. The assistant forgot the student who knew that the exam was important **was standing** in the hallway.

The ambiguity manipulation ensures that reanalysis takes place at *was standing*—the NP *the student* must be reanalyzed as the subject of a sentential complement rather than the object of *forgot*. The distance manipulation ensures that the reattachment of the NP as subject of *was standing* is affected by locality.

However, the reanalysis also requires a locality-based integration between the verb and the argument. Consequently, if a significantly greater reanalysis cost is observed in the intervening-items conditions (9c,d) than in the non-intervening-items conditions (9a,b), this would be a locality effect, and it would be independent of spillover confounds because the comparison is no longer a direct one between conditions with differing regions preceding the critical verb. The interaction was indeed observed in the Van Dyke and Lewis study, suggesting that locality can affect processing.

Summarizing the above discussion, although intervention-based speedups observed in Hindi are affected significantly by spillover from the preceding region, the speedups remain after this spillover is factored out.[12] This speedup effect is problematic for the central assumptions of locality-based theories, but, as Grodner and Gibson have argued, it could in principle be explained by an orthogonal dimension: a dependent relation between intervener and verb causing a preactivation of a verb, or some indirect relation (e.g. causal) between the intervening region and the verb. Other research (Jaeger et al. 2005) has found antilocality effects in English as well. Since Jaeger and colleagues held constant the region preceding the critical one, it is likely that the locality effects found in English are due to a spillover confound. By contrast, locality costs do show up in other studies that manipulate distance indirectly, as Van Dyke and Lewis did.

We turn now to the issue of explaining the precise source of anticipation. Note that Konieczny's time-based facilitation hypothesis would incorrectly predict a lower reanalysis cost in 9c,d than in the non-intervening-items conditions 9a,b, since greater time is available in the intervening-items conditions. We are therefore left only with Grodner and Gibson's intervener-verb relations hypothesis. It is quite straightforward to incorporate this idea into any locality-based theory such as DLT: one can simply additively enrich the theory by positing a benefit due to, for example, the predictability of the argument structure of the upcoming verb. This appears to be completely reasonable, since the effect on processing of factors like lexical frequency is also explained as an additional effect on top of the core assumption of locality.

A more parsimonious approach, however, would be if independently motivated theoretical assumptions can explain both processing slowdowns like those in Van Dyke & Lewis 2003 and speedups observed in the experiments presented here. We now briefly present such a theory.

5. AN ALTERNATIVE ACCOUNT. Experimental and theoretical work in cognitive psychology gives us very general, modality- and task-independent characterizations of human information processing. Among them are the ideas of activation decay and interference. Although decay and interference have long been considered to be competing explanations for forgetting (e.g. Brown 1958, Peterson & Peterson 1959, Keppel & Underwood 1962, Waugh & Norman 1965), there is evidence supporting the idea that both factors play a role in information processing (see Anderson & Lebiere 1998, Altmann & Schunn 2002 and references cited there).

Under one such view, developed by Anderson and colleagues (2004), the ability to use an item in real-time processing can be described in terms of its activation level. Highly active items can be accessed and recalled more quickly, and activation can be increased by repeated access. But activation can be attenuated by similarity: the more items involved that are mutually similar along some dimension, the harder it is to access any one of them.

Equation 10 formalizes the idea of activation values fluctuating over time, with activation reflecting usage history and time-based decay. The equation says that the base-level activation B_i of item i is dependent on the number of times n that it has been retrieved, the amount of time that has elapsed since the jth retrieval, with activation decay between retrievals defined in terms of the parameter d (Anderson and Schooler (1991) present a detailed justification).

[12] An interesting open question is whether the speedup observed in the German data (Konieczny 2000) remains after spillover is factored out. This would require either a reanalysis of the existing Konieczny data or a replication of that study.

$$(10)\ B_i = \ln\left(\sum_{j=1}^{n} t_j^{-d}\right)$$

The notion of similarity affecting activation can be operationalized in terms of associative retrieval interference: when an item needs to be retrieved from memory by means of some retrieval cue, the strength of association from the cue is reduced as a function of the number of items *j* associated with the cue. This is captured by equation 11, which reduces the maximum associative strength *S* from item *j* to cue *i* by the log of the 'fan' of item *j*, that is, the number of items associated with *j*.

$$(11)\ S_{ji} = S - ln\ (\text{fan}_j)$$

For example, if only one item is associated with a retrieval cue, and if $S = 3$, then the strength of association S_{ji} between item *j* and cue *i* will be $3 - ln(1) = 3 - 0 = 3$. If two items are associated with the cue *i*, then S_{ji} will be $3 - ln(2) = 3 - 0.7 = 2.3$. In the psychology literature, this decrease in associative strength as a function of the number of associated items is known as the 'fan' effect (Anderson et al. 2004).

The activation A of an item *i* is computed by equation 12, and the latency of retrieval depends on its activation; this is defined in equation 13. The terms *F*, *W*, *S*, and *d* in equations 10–12 are numerical parameters with fixed values (Lewis & Vasishth 2005).

$$(12)\ A_i = B_i + \sum_j W_j S_{ji}$$

$$(13)\ \text{Time}_i = Fe^{-A_i}$$

These equations can explain a range of phenomena in human information processing, going far beyond (but including) sentence processing. They form an integral part of an implemented cognitive architecture known as ACT-R, which has been used successfully in mathematical psychology and computational modeling for modeling human cognitive processes (see Anderson et al. 2004 for references to relevant work). Elsewhere (Lewis & Vasishth 2005) we provide a detailed specification of an ACT-R-based sentence-processing model and demonstrate its effectiveness in modeling moment-by-moment human parsing processes.

The effect of activation decay is illustrated schematically in Figure 10 with reference to experiment 1's results. Assume that a predicted embedded VP node is created at the fourth NP, and that it is retrieved at the adverb and then at the verb itself. This amounts to a total of three boosts in activation (once during creation, which counts as a retrieval in the ACT-R theory (Anderson et al. 2004), then two retrievals). This retrieval schedule is simulated in Fig. 10.

Boosts can be attenuated by the interference effect: if one or more other item matches the cue(s) driving a retrieval event, the activation of these items gets damped by equation 11 above. The result is that the item to be retrieved has a lower activation, resulting in a slower retrieval (longer processing time) during the retrieval event.

We assume that processing costs during parsing are a function of these constraints on activation. Following the standard assumption in the literature (Johnson-Laird 1983, Crocker 1999), we also assume that parsing is driven by a combination of top-down (predictive) and bottom-up mechanisms. One such mechanism is serial left-corner (LC) parsing (Aho & Ullman 1972). In essence, a left-corner parser takes as input a lexical item and uses the grammar specification to build up a tree that contains predicted nonterminal nodes. For example, a string like *the woman* at the beginning of a sentence results in (i) an NP node being built (a bottom-up step), and (ii) a prediction for a sentence containing the NP and an as-yet unseen intransitive verb phrase (a top-down step). If instead of an intransitive a transitive verb is seen next, the predicted VP is modified and an object NP is predicted.

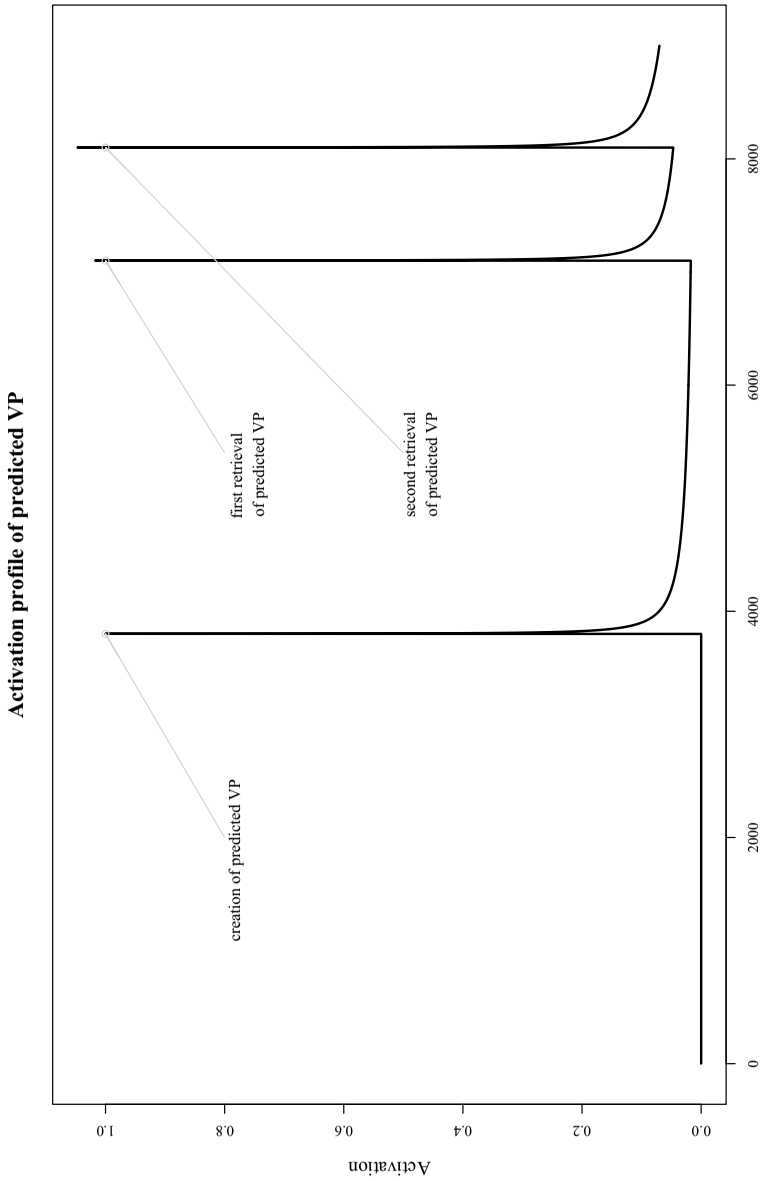

FIGURE 10. Simulation showing effect of activation decay and reactivation due to retrieval.

The predicted nodes constructed bottom-up and top-down are interdependent chunks that are related by referencing daughter nodes as feature values in the mother node (see Figure 11). Each node, from the point of its creation in the tree, is subject to equations 10–13. Therefore, the retrieval of any node, such as an NP or VP, is a function of its activation.

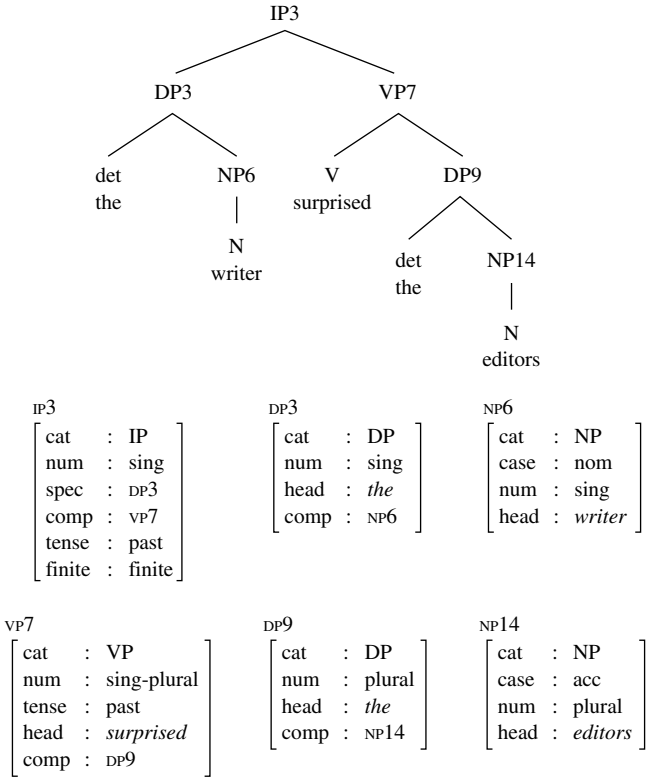

FIGURE 11. Example of a tree representation of *The writer surprised the editors* and the corresponding items in memory that encode that tree.

When the verb is processed, two things happen: (i) the predicted VP is retrieved for syntactic integration of the verb with the predicted node, and (ii) the verb's argument NPs are retrieved for semantic integration with the verb. If some event causes the retrieval of an NP or VP node before its retrieval at a verb, because of equation 10 the activation of that node will increase and its subsequent retrieval at the verb will be faster. One such situation occurs when a relative clause intervenes between the verb and the NP—the NP must be retrieved to attach the modifying RC. Similarly, if a PP or an adverb appears between the NP and the verb, the predicted VP must be retrieved in order to attach the VP-modifier. These two kinds of interveners would result in faster retrieval of the NP (if the RC intervenes) and a faster subsequent retrieval of the predicted VP (if a PP or adverb intervenes). This mechanism accurately models the Hindi results: in experiment 1, the intervening material modifies either the last NP or the predicted VP, thereby reactivating it; in experiment 2, the intervening material contains a verb that reactivates the subject NP as well as attaching to the predicted VP.

The model also predicts slowdowns, but under specific conditions. One situation would be where the intervening material takes too long to process. Here, decay would

counteract any advantage due to the increased NP or VP activation. Such a result was indeed found by Christianson (2002). Slowdowns are also predicted when the intervening item does not reactivate a predicted or previously seen node. Evidence for slowdowns comes from the experiment by Van Dyke and Lewis described above; the distance effect is manifested there in reanalysis-distance interaction (see also Lewis & Vasishth 2005 for a detailed computational model of these results).

A further prediction emerges from the interference equation. If multiple NPs have been processed that have some feature in common (such as [+human]) and a verb is seeking an NP with that feature (i.e. sets a retrieval cue for a [+human] NP), increased difficulty in retrieving the target NP is predicted. In this situation, if an NP gets highly activated due to an intervening RC having attached to it, this increase in activation could be canceled by the increase in retrieval interference if another, similar NP has also been processed. As a result, neither a speedup or a slowdown should be seen at the verb. A theory relying on argument-head distance would not predict any such retrieval interference effects.

Presented next is an experiment that evaluates this prediction by maintaining a high degree of interference and varying the amount of facilitation.[13]

6. EXPERIMENT 3. In experiment 2, NP1 and NP2 were of distinct types in the sense that the relative clause's subject had a human referent and the direct object an inanimate referent. In order to investigate the opposing effects of anticipation-driven facilitation versus greater retrieval interference, a third self-paced reading experiment was carried out by modifying the stimuli in experiment 2 so that both NP1 and NP2 were human-referring. Example stimuli for this experiment are given in 14.

(14) a. Vo dukaandaar jisko us laṛke-ne dekhaa bahut amiir thaa.
that shopkeeper whom that boy-ERG saw very rich was
'That shopkeeper whom that boy saw was very rich.'

b. Vo laṛkaa jisne us dukaandaar-ko dekhaa bahut jigyaasu thaa.
that boy who that shopkeeper-ACC saw very inquisitive was
'That boy who saw that shopkeeper was very inquisitive.'

c. Vo dukaandaar jisko us laṛke-ne **mez-ke saamne khaṛe.hue**
that shopkeeper whom that boy-ERG table-GEN in.front standing
dekhaa bahut amiir thaa.
saw very rich was
'That shopkeeper whom that boy saw standing in front of a/the table was very rich.'

d. Vo laṛkaa jisne us dukaandaar-ko **mez-ke saamne khaṛe.hue**
that boy who that shopkeeper-ACC table-GEN in.front standing
dekhaa bahut jigyaasu thaa.
saw very inquisitive was
'That boy who saw that shopkeeper standing in front of a/the table was very inquisitive.'

Here, the region of interest is the innermost verb (V2). The verb sets a retrieval cue for, inter alia, a [+human] NP subject. Since two [+human] NPs are present, their activation is reduced because of the interference equation 11. In addition, if some NP-modifying material intervenes between the final NP and the verb, this increases the

[13] A more direct test would be to vary the amount of interference as well as facilitation. We plan to explore this and other manipulations in further studies.

final NP's activation. Making the simplest assumption that interference and facilitation have an equal and opposing effect, the net result should be no change in activation of the second NP when it is modified.

6.1. RESULTS AND DISCUSSION. The first contrast analysis concerned the effect of increasing argument-head distance in object relatives; see examples 14a,c and Figure 12.

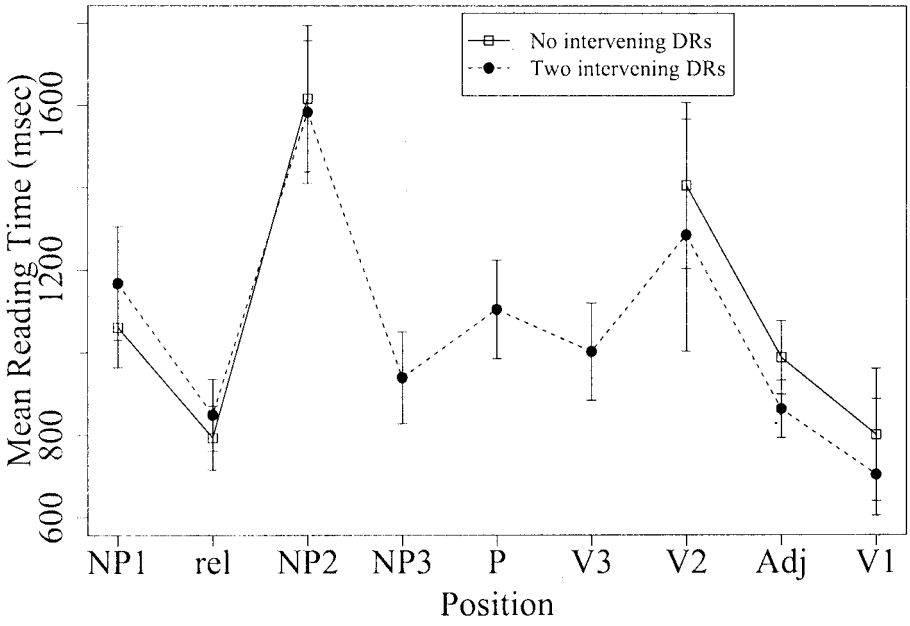

FIGURE 12. Phrase-by-phrase reading times in experiment 3, object relatives; 95% confidence intervals.

In this experiment, unlike experiment 2, the difference in reading time at V2 for the two conditions did not reach significance ($F1(1,43) = 0.16$, $p = 0.7$; $F2(1,23) = 0.10$, $p = 0.8$). The second contrast analysis looked at the effect of increasing argument-head distance in subject relatives; see examples 14b,d and Figure 13. Here too, the difference at V2 failed to reach significance ($F1(1,43) = 2.28$, $p = 0.14$; $F2(1,23) = 0.78$, $p = 0.4$).

The residuals correction for spillover was carried out as in earlier experiments, and the results are as follows. In the object relative clauses, the difference between the no-intervention and intervention conditions remained nonsignificant at the critical region V2 ($F1(1,43) = 0.09$, $p = 0.8$; $F2(1,23) = 0.62$, $p = 0.4$), and the same was true for subject relatives ($F1(1,43) = 0.52$, $p = 0.5$; $F2(1,23) = 0.34$, $p = 0.6$). In the postcritical region all differences were nonsignificant: object relative contrasts were $F1(1,43) = 2.47$, $p = 0.12$; $F2(1,23) = 2.40$, $p = 0.14$; and subject relative contrasts were $F1(1,23) = 1.72$, $p = 0.2$; $F2(1,23) = 3.45$, $p = 0.08$. No group effects were observed in any of the contrast analyses.

The linear mixed-effects model for the critical region showed no effect of intervention in object relatives ($F1(1,43) = 0.22$, $p = 0.64$; $F2(1,20) = 0.53$, $p = 0.47$), a spillover effect ($F1(1,372) = 22.14$, $p < 0.0001$; $F2(1,418) = 36.75$, $p < 0.0001$), and an interaction only in the by-items ($F1(1,372) = 2.067$, $p = 0.15$; $F2(1,418) = 4.00$, p

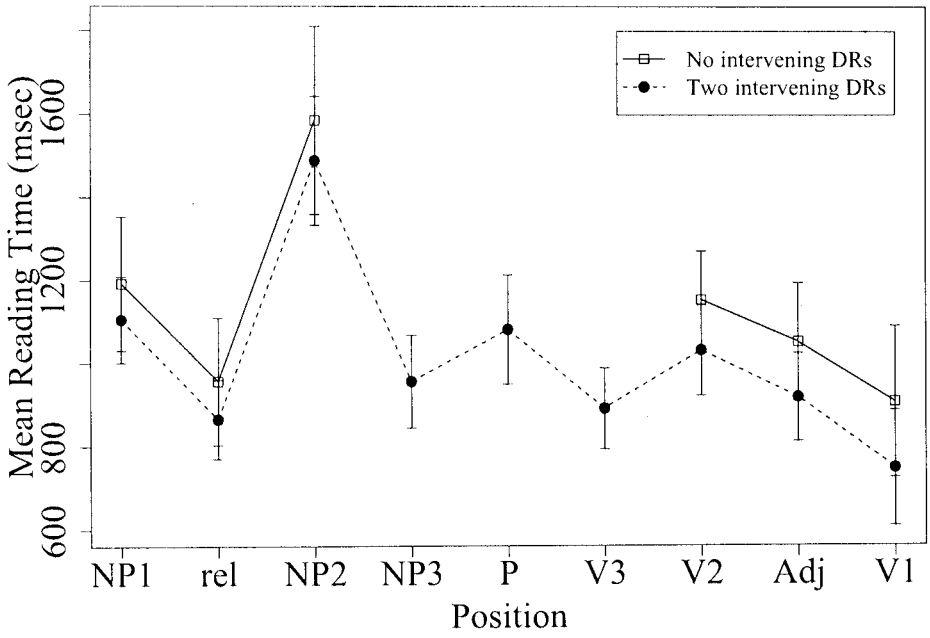

FIGURE 13. Phrase-by-phrase reading times in experiment 3, subject relatives; 95% confidence intervals.

= 0.05). The subject relatives also showed no intervention effect ($F1(1,43) = 2.20$, $p = 0.2$; $F2(1,20) = 1.88$, $p = 0.2$), a spillover effect ($F1(1,372) = 28.82$, $p < 0.0001$; $F2(1,418) = 41.40$, $p < 0.0001$), and an interaction only in the by-items ($F1(1,372) = 2.81, p = 0.1; F2(1,418) = 4.26, p = 0.04$). Table 4 presents a summary.

INTERPOSED ITEM	INTERVENTION EFFECT	SPILLOVER EFFECT	INTERACTION
Object relatives	× ×	√ √	× √
Subject relatives	× ×	√ √	× √

TABLE 4. Summary of linear mixed-effects model analysis at the main verb (V2) in experiment 3. See Table 1 for explanation of marks and column headings.

In the postcritical region the object relatives showed an effect of intervention ($F1(1,43) = 5.14$, $p = 0.03$; $F2(1,20) = 5.23$, $p = 0.03$), a main effect of spillover ($F1(1,372) = 4.59$, $p = 0.03$; $F2(1,418) = 5.71$, $p = 0.02$), and an interaction ($F1(1,372) = 6.07$; $p = 0.02$; $F2(1,418) = 8.16$, $p = 0.005$). The subject relatives, by contrast, showed no effect of intervention ($F1(1,43) = 2.05$, $p = 0.16$; $F2(1,20) = 2.30$, $p = 0.15$), but did show a main effect of spillover ($F1(1,372) = 11.03$, $p = 0.001$; $F2(1,418) = 14.97$, $p = 0.0001$), and only a marginal interaction ($F1(1,372) = 3.22$, $p = 0.07$; $F2(1,418) = 4.73$, $p = 0.03$). See Table 5 for a summary.

INTERPOSED ITEM	INTERVENTION EFFECT	SPILLOVER EFFECT	INTERACTION
Object relatives	√ √	√ √	√ √
Subject relatives	× ×	√ √	× √

TABLE 5. Summary of linear mixed-effects model analysis in the postcritical region (Adj) in experiment 3. See Table 1 for explanation of marks and column headings.

Experiment 3 thus suggests that increasing SBI may be able to nullify any anticipation-driven facilitation to some extent: if, unlike experiment 2, NP1 and NP2 are both

human-referring noun phrases, we do not find a significantly shorter reading time at V2 when argument-head distance is increased.

7. CONCLUSION. This article presented two experiments that extend previous work by providing evidence for anticipation-based facilitation. A theory was presented which provides an explanation for the phenomena based on existing assumptions in cognitive psychology about constraints on activation. One prediction of the proposed theory, a modulation of anticipatory facilitation by similarity-based interference, is supported by a third experiment.

Constrained activation is thus the proposed alternative to locality-driven complexity metrics that rely on argument-head distance. There are several differences between these two approaches. First, the activation-based approach does not posit a metric relevant only to sentence processing; it applies to a wide range of information-processing tasks (Anderson et al. 2004). Second, the speedup effect is explained by a central assumption of the theory, activation boost due to multiple retrievals, and slowdown effects can be explained by decay. Finally, activation can be attenuated by the independently motivated interference equation 11. By contrast, locality-based accounts would need to go beyond the core architecture of the theory in order to account for the speedup, slowdown, and interference facts discussed here and in other research.

In conclusion, although it is clear that locality plays a critical role in sentence comprehension, the processing cost associated with increasing argument-head distance appears to be modulated by several factors, such as similarity-based interference and anticipation. We argue that locality, anticipation, and interference are best characterized in terms of very general constraints on activation of items in memory.

APPENDIX: EXPERIMENT STIMULI

EXPERIMENT 1. Shown below are the stimuli used for experiment 1. The first example (1a) provides a full gloss with an English translation; all other stimulus items present only transcriptions in order to save space. The three intervention conditions are shown separated by forward-slashes.

(1) a. Ruchi-ne Sita-ko Hari-ko us kitaab-ko jitnii jaldii ho sake/ ek acchii dukaan-se/
Ruchi-ERG Sita-DAT Hari-DAT that book-ACC as soon as possible a good shop-from
jo dukaana-me thii khariid-neko kaha-neki salaah dii.
that shop-in was buy-INF say-INF advice gave
'Ruchi advised Sita to tell Hari to buy that book as soon as possible/from a good shop/which was in the shop.'

b. Rita-ne Seema-ko Ravi-ko us ghar-ko saat baje-se pahale/ ek acche ejeṇṭ-ke
Rita-ERG Seema-DAT Ravi-DAT that house-ACC seven o'clock before a good agent-GEN
dvaaraa/ jo graahaka-ko pasand thaa bec-neko uksaa-nekaa sujhaav diyaa.
from that customer-ACC liked was sell-INF incite-INF suggestion gave

c. Ruchi-ne Kanta-ko Sunita-ko us roṭi-ko jitnii jaldii ho sake/ thaalii-par
Ruchi-ERG Kanta-DAT Sunita-DAT that bread-ACC as soon as possible plate-on
rakhkar/ jo thaalii-par thii khaa-neko bol-neko kahaa.
putting.after that plate-on was eat-INF say-INF said

d. Punita-ne Prabal-ko Anil-ko us caabii-ko bahut dhyaan-se/ zamiin-se/ jo
Punita-ERG Prabal-DAT Anil-DAT that key-ACC very carefully ground-from that
zamiin-par thii uṭhaa-neko aadesh de-neko bolaa.
ground-on was pick.up-INF order give-INF said

e. Gita-ne Abhay-ko Aruna-ko us zahar-ko sab-ke saamne almaarii-se
Gita-ERG Abhay-DAT Aruna-DAT that poison-ACC everyone-GEN front.of cupboard-from
nikaalkar/ jo almaarii-me thii pii-neko uksaa-neko kahaa.
taking.out that cupboard-in was drink-INF incite-INF said

f. Prakash-ne Ritu-ko Umesh-ko us kaar-ko binaa jaldii kiye/ peṛ-kii or/ jo
Prakash-ERG Ritu-DAT Umesh-DAT that car-ACC without hurrying tree-GEN toward that

peṛ-ke saamne thii calaa-neko kah-nekii nasiihat dii.
tree-GEN front.of was drive-INF say-INF advice gave

g. Ramita-ne Lata-ko Dilip-ko us dukaan-ko binaa jaldii kiye/ duurbiin-se/ jo
Ramita-ERG Lata-DAT Dilip-DAT that shop-ACC without hurrying telescope-with that
duurbiin-ke paas thii dekh-neko salaah de-neko bolaa.
telescope-GEN near was see-INF advice give-INF told

h. Lata-ne Kapil-ko Sandip-ko us kambal-ko ṭhiik tarah-se/ bistar-se lekar/ jo
Lata-ERG Kapil-DAT Sandip-DAT that blanket-ACC properly bed-from taking that
bistar-par paṛaa thaa oṛh-neko nasiihat de-neko bolaa.
bed-on lying was cover-INF advice give-INF told

i. Seema-ne Ramesh-ko Ila-ko us saamaan-ko dhyaan-se/ mez-par rakhne-ke baad/
Seema-ERG Ramesh-DAT Ila-DAT that luggage-ACC carefully table-on put-GEN after
jo mez-par rakhaa-huaa thaa khol-neko hukma de-neko bolaa.
that table-on kept was open-INF order give-INF told

j. Pramod-ne Naresh-ko Ravi-ko us patra-ko aaraam-se/ pichle-vaale kamre-me/
Pramod-ERG Naresh-DAT Ravi-DAT that letter-ACC slowly back room-in
jo kamre-me gum ho gayaa thaa khoj-neko sujhaav de-neko bolaa.
that room-in lost was find-INF suggestion give-INF told

k. Ashok-ne Kamla-ko Anuj-ko us kaagaz-ko jaldii-se/ patthar-par rakhkar/
Ashok-ERG Kamla-DAT Anuj-DAT that (piece.of).paper-ACC quickly stone-on putting
jo patthar-par rakhaa thaa jalaa-neko salaah de-neko aadesha diya.
that stone-on kept was burn-INF suggestion give-INF order gave

l. Savita-ne Malti-ko Indar-ko us caay-ko ṭhiik tarah-se/ rasoii ghara-me/ jo
Savita-ERG Malti-DAT Indar-DAT that tea-ACC properly kitchen-in that
rasoii ghara-me thii banaa-neko aadesh de-neko kahaa.
kitchen-in was make-INF order give-INF told

m. Rahul-ne Alak-ko Sudhir-ko us kalam-ko acchii tarah-se/ kaagaz-ke niice/ jo
Rahul-ERG Alak-DAT Sudhir-DAT that pen-ACC thoroughly paper-GEN under that
kaagaz-ke niice thaa chipaa-neko kah-neko uksaayaa.
paper-GEN under was hide-INF say-INF incited

n. Abhay-ne Jayant-ko Kusum-ko us paanii-ko das mineṭ-ke liye/ choṭe-vaale
Abhay-ERG Jayant-DAT Kusum-DAT that water-ACC ten minutes-GEN for small
bartan-me/ jo choṭe-vaale bartan-me thaa ubaal-neko ijaazat de-neko kahaa.
utensil-in that small utensil-in was boil-INF permission give-INF told

o. Rahul-ne Tanuja-ko Sudip-ko us patang-ko josh-se/ khule maidaan-me/
Rahul-ERG Tanuja-DAT Sudip-DAT that kite-ACC enthusiastically open field-in
jo maidaan-me thii uḍaa-neko aadesh de-neko kahaa.
that field-in was fly-INF order give-INF told

p. Girish-ne Jyoti-ko Raj-ko us giit-ko josh-se/ guruji-se ijaazat
Girish-ERG Jyoti-DAT Raj-DAT that song-ACC enthusiastically teacher-from permission
lekar/ jo guruji-ne likhaa thaa sunaa-neko raay de-neko kahaa.
taking that teacher-ERG written had sing-INF advice give-INF told

q. Gita-ne Jyoti-ko Yashpal-ko us koṭ-ko jitnii jaldii ho sake/ kamre-me laane-ke
Gita-ERG Jyoti-DAT Yashpal-DAT that coat-ACC as soon as possible room-in bringing
baad/ jo kamre-me rakhaa thaa pahan-neko nasiihat de-neko kahaa.
after that room-in lying was wear-INF advice give-INF told

r. Harpal-ne Lokesh-ko Tejal-ko us daal-ko saat baje-se pahale/ degcii-me/
Harpal-ERG Lokesh-DAT Tejal-DAT that lentil-ACC seven o'clock-from before pot-in
jo degcii-me thii pakaa-neko kaha-neko bolaa.
that pot-in was cook-INF say-INF said

s. Gita-ne Jyotsna-ko Omprakash-ko us ṭaayar-ko ṭhiik tarah-se/ ghar-ke
Gita-ERG Jyotsna-DAT Omprakash-DAT that tire-ACC properly house-GEN
saamne/ jo ghar-ke saamne paṛaa thaa badal-neko hukm de-neko bolaa.
in.front.of that house-GEN in.front.of lying was change-INF order give-INF told

t. Gita-ne Divya-ko Uttam-ko us bas-ko jitnii jaldii ho sake/ saṛak-ke biic-me/
Gita-ERG Divya-DAT Uttam-DAT that bus-ACC as soon as possible street-GEN middle-in
jo saṛak-se aa rahii thii rok-neko bol-neko kahaa.
that street-from coming was stop-INF say-INF told

u. Kanta-ne Niti-ko Manish-ko us seb-ko dhyaan lagaakar/ thaalii-par
Kanta-ERG Niti-DAT Manish-DAT that apple-ACC carefully plate-on
rakhkar/ jo thaalii-par thii chiil-neko bol-neko kahaa.
putting.after that plate-on was peel-INF say-INF told

v. Hari-ne Jitendra-ko Ramita-ko us rassii-ko zor lagaakar/ peṛ-par laṭkaakar/
Hari-ERG Jitendra-DAT Ramita-DAT that rope-ACC with force tree-on hanging.after
jo peṛ-par laṭkii thii toṛ-neko uksaa-neko kahaa.
that tree-on hanging was break-INF incite-INF told

w. Kapil-ne Tara-ko Padma-ko us gilaas-ko binaa galtii kiye/ zamiin-par
Kapil-ERG Tara-DAT Padma-DAT that glass-ACC without making a mistake ground-on
rakhkar/ jo zamiin-par rakhaa thaa joṛ-neko ijaazat de-neko bolaa.
putting.after that ground-on lying was fix-INF permission give-INF told

x. Neha-ne Tapan-ko Payal-ko us caadar-ko acchii tarah-se/ diivaar-par
Neha-ERG Tapan-DAT Payal-DAT that bedsheet-ACC properly wall-on
bichaakar/ jo diivaar-par bichii thii sukhaa-neko kaha-neko bolaa.
spreading.after that wall-on spread was dry-INF say-INF told

EXPERIMENT 2. In the list below, the strings shown are the first and second NPs of the object relatives, the intervening phrase, the verb, and the postverbal adjectival phrase (for object and subject relatives, respectively). The final word, not shown here, was always the auxiliary verb. The full sentence for each condition can be assembled by adding the function words as shown earlier in example 6.

(2) a. kaagaz laṛkaa/ mez-ke piiche gire hue/ dekhaa bahut puraanaa/ amiir
(piece.of).paper boy fallen behind the table saw very old rich

b. patr laṛki/ shabdkosh-ke andar cipke hue/ dekhaa bahut dilachasp/ jigyaasuu
letter girl stuck inside a dictionary saw very interesting curious

c. churii pulisvaalaa/ kaaliin-ke uupar ghasiiṭkar/ uṭhaayaa bahut tez/ akalmand
knife policeman after dragging over the carpet picked.up very sharp clever

d. vaahan aadamii/ bas-ki madad-se rokakar/ bacaayaa bahut kiimtii/ moṭaa
vehicle man stopped with the help of the bus saved very expensive fat

e. mez shikshak/ baazaar-me dekhkar/ le liyaa bahut acchii/ laalcii
table teacher after seeing in the market took very nice greedy

f. diivaan graahak/ ghar-ke andar laate hii/ vaapas kar diyaa bahut baṛaa/ amiir
couch customer soon after bringing into the house returned very big rich

g. caarpaaii dukaandaar/ saṛak-ke biic-me rakhkar/ ṭhiik kiyaa bahut choṭii/ lobhii
bed shopkeeper after putting in the middle of the street fixed very small greedy

h. botal mazaduur/ nahar-me khaalii karke/ saaph kiyaa bahut bhaarii/ gariib
bottle worker after emptying it into the stream cleaned very heavy poor

i. haar laṛkii/ khiṛkii-ke paas camakte hue/ dekhaa bahut sundar/ utsuk
necklace girl glistening near the window saw very beautiful curious

j. laaiṭ balb munshii/ almaarii-ke andar-se nikaalkar/ lagaayaa tiin sau vaaṭ-kaa/ bahut hii
light bulb clerk after taking out of the cupboard attached 300 Watts very
akalmand
clever

k. baalṭii caukiidaar/ kone-kii taraph ghasiiṭkar/ bharaa kaale rang-kii/ bahut thakaa huaa
bucket watchman after dragging to the corner filled black-colored very tired

l. phuuldaan halvaaii/ tasviir-ke saamane khaṛaa karake/ saaph kiyaa sundar/ moṭaa
vase sweets vendor after placing in front of the picture cleaned beautiful fat

m. cammac nars/ jeb-ke andar-se nikaalkar/ dhoyaa bahut gandaa/ jaldii me
spoon nurse after taking out of pocket washed very dirty in a hurry

n. maṭkaa maalii/ ghar-ke piiche dhokar/ camkaayaa piital-kaa banaa/ bahut
vessel gardener after washing behind the house polished made from copper very
kamzor
weak

o. belan khaansaamaa/ thaalii-ke uupar rakhkar/ joṛaa ekdam nayaa/ kaafii khush
rolling.pin cook after putting on the plate fixed absolutely new quite happy

p. aam mazaduur/ churii-ko istemaal karke kaaṭkar khaayaa kaaphii acchaa/ bahut patlaa
mango worker after cutting with a knife ate very nice very thin

q. jhaaṛan adhyaapak/ paanii-ke andar-se nikaalkar/ pakṛaa laal rang-kaa/ lambe kad-kaa
mop teacher after taking out of water grabbed red-colored tall

r. phaaṭak ḍaakiyaa/ saikal-kii madad-se dhakelkar/ kholaa kaaphii baṛaa/ bahut jaladii-me
gate postman after pushing using the bicycle opened quite big in a big hurry
s. rediyo kisaan/ khiṛkii-ke uupar rakhkar/ sunaa choṭaa-saa/ samacaar-ke liye betaab
radio farmer after putting on the window heard small eager to hear the news
t. koṭ ḍaakṭar/ almaarii-ke andar ṭaangkar/ chipaayaa kisii aur-kaa/ bahut laalcii
coat doctor after hanging in the cupboard hid someone else's very greedy
u. ṭahanii lakaṛhaaraa/ maidaan-ke biic-me laakar/ jalaayaa bahut bhaarii/ jaldii me
branch woodcutter after bringing to the center of the field burnt very heavy in a hurry
v. ṭiivii mantrii/ afsar-se maangkar/ istemaal kiyaa bahut kiimtii/ beimaan
TV minister after asking for from the officer used very expensive dishonest
w. kangii abhinetaa/ daraaz-ke piiche-se nikaalkar/ toṛaa sone-kii banii/ paagal ho gayaa
comb actor after taking out from behind the drawer broke made of gold had gone mad
x. kamiiz bhikhaarii/ kiicaṛ-ke andar-se nikaalkar/ dhoyaa bilkul nayii/
shirt beggar after taking out of the puddle of dirty water washed absolutely new
bahut dubalaa
very thin

EXPERIMENT 3. The list of items shows the first and second NPs, the intervening phrase, the verb, and the postverbal adjectival phrase (for object and subject relatives, respectively). The final segment, not shown here, was always the auxiliary verb *thaa*.

(3) a. naukar laṛkaa/ ghar-ke piiche bulaakar/ dekhaa bahut dublaa
servant boy after calling behind the house saw very thin
b. baalak laṛkii/ khilaune-ke saath leṭaakar/ giit sunaayaa bahut dilchasp
boy girl after laying down next to the toy song sang very interesting
c. pulisvaalaa mainejar/ kaaliin-ke uupar giraakar/ piiṭaa bahut gusse-vaalaa
policeman manager after throwing onto the carpet beat up very angry
d. aadmii phalvaalaa/ chat-ke uupar pakaṛkar/ bacaayaa bahut moṭaa
man fruit.seller caught at the roof saved very fat
e. chaatr shikshak/ saṛak-ke biic-me rokakar/ paise diye bahut acchaa
student teacher stopped in the street money gave very nice
f. muniim graahak/ ghar-ke andar laate hii/ vaapas bhej diyaa bahut ghabraayaa huaa
clerk customer soon after bringing into the house sent back very worried
g. dukaandaar sipaahii/ saṛak-ke biic-me rokakar/ paise diye bahut lobhii
shopkeeper soldier after stopping in the middle of the street money gave very greedy
h. mazduur giitkaar/ galii-ke andara le jaakar/ maaraa bahut gariib
worker singer after taking into the side-street beat very poor
i. kaarigar baccaa/ maidaan-ke andar bulvaakar/ dekhaa bahut javaan
artisan boy after calling into the field saw very young
j. munshii naaii/ dukaan-ke andar-se bulaakar/ inaam diyaa bahut hii akalmand
clerk barber after calling from inside the shop prize gave very clever
k. kisaan caukiidaar/ khet-ke us paar-se bulaakar/ cetaavnii dii bahut kaabil
farmer watchman after calling from across the field warning gave very capable
l. halvaaii sangiitkaar/ dukaan-ke piiche-se fon karke/ bulaayaa moṭaa
sweets.vendor singer phoned from behind the shop called fat
m. senaapatii nars/ haspataal-ke baahar bulaakar/ davaa dii bahut biimaar
general nurse after have come over outside the hospital medicine gave very ill
n. paayleṭ maalii/ ghar-ke saamne rokakar/ raastaa bataayaa jaldii-me
pilot gardener after stopping in front of the house way showed in a hurry
o. khaansaamaa bas kanḍakṭar/ sṭeshan-ke saamne rokakar/ paise diye kaaphii khush
cook bus conductor after stopping in front of the station money gave quite happy
p. mazduur vaahan caalak/ bhiiṛ-ke saamne ghasiiṭakar/ maaraa bahut patlaa
worker driver after dragging in front of the crowd beat very thin
q. machuaaraa adhyaapak/ nadii-ke andar-se nikaalkar/ bacaayaa ghabraayaa-huaa
fisherman teacher after pulling out of water saved distraught
r. ḍaakiyaa vakiil/ ghar-ke andar bulaakar/ patr diyaa bahut jaldii-me
postman lawyer after bringing into house letter gave in a big hurry
s. afasar banjaaraa/ peṛ-ke paas bulaakar/ dekhaa gusse-me
officer gypsy after calling to the vicinity of the tree saw angry

t. darshak ḍaakṭar/ haal-ke bhiitar-se dhakelakar/ bhagaayaa bahut battamiiz
spectator doctor after pushing out of the hall made go away very rude
u. lakaṛhaaraa ṭiicar/ peṛ-ke uupar dekhkar/ bacaayaa acchaa aadamii
woodcutter teacher after seeing on the tree saved good person
v. baink adhikaarii mantrii/ kamre-ke andara laakar/ paise diye bahut badmaash
bank officer minister after bringing home money gave very wicked
w. abhinetaa vaahan caalak/ film seṭ-ke baahar le jaakar/ salaah dii bahut dilacasp
actor driver after taking him out from the film set advice gave very interesting
x. sharaabii bhikhaarii/ kiicaṛ-se nikaalkar/ bacaayaa acchaa aadmii
drunkard beggar after pulling out of the puddle of dirty water saved good man

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