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Agreement attraction in comprehension: Representations and processes

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ABSTRACT

Much work has demonstrated so-called attraction errors in the production of subject–verb agreement (e.g., ‘The key to the cabinets are on the table’, [Bock, J. K., & Miller, C. A. (1991). Broken agreement. *Cognitive Psychology*, 23, 45–93]), in which a verb erroneously agrees with an intervening noun. Six self-paced reading experiments examined the online mechanisms underlying the analogous attraction effects that have been shown in comprehension; namely reduced disruption for subject–verb agreement violations when these ‘attractor’ nouns intervene. One class of theories suggests that these effects are rooted in faulty representation of the number of the subject, while another class of theories suggests instead that such effects arise in the process of re-accessing subject number at the verb. Two main findings provide evidence against the first class of theories. First, attraction also occurs in relative clause configurations in which the attractor noun does not intervene between subject and verb and is not in a direct structural relationship with the subject head (e.g., ‘The drivers who the runner wave to each morning’). Second, we observe a ‘grammatical asymmetry’: attraction effects are limited to ungrammatical sentences, which would be unexpected if the representation of subject number were inherently prone to error. We argue that agreement attraction in comprehension instead reflects a cue-based retrieval mechanism that is subject to retrieval errors. The grammatical asymmetry can be accounted for under one implementation that we propose, or if the mechanism is only called upon when the predicted agreement features fail to be instantiated on the verb.

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Introduction

The trajectory of language processing reflects sophisticated grammatical knowledge that takes advantage of complex structural cues. However, some of our best information about the processing architecture comes when its seams are exposed by characteristic ‘mistakes’. The formulation of agreement in language production is one domain famously prone to such a class of mistakes, commonly known as agreement attraction. In agreement attraction errors, an agreement-bearing element, such as a verb, fails to match the agreement features of its grammatical con-

troller and instead realizes agreement with a nearby but grammatically inaccessible distractor. In the example in (1) the plural number feature of the verb *make* mismatches with the singular number of the subject noun phrase ‘the sheer weight of all these figures’ and instead matches an NP within the subject-internal prepositional phrase.

- (1) [_{NP} The sheer weights_{SG} [_{PP} of all these figures_{PL}]]
make_{PL} them harder to understand
(based on Ronald Reagan, 13 October 1982; quoted in Francis (1986).

Examples like these have long been noticed by grammarians and syntactic theorists (den Dikken, 2001; Francis, 1986; Jespersen, 1924; Kimball & Aissen, 1971; Quirk, Greenbaum, Leech, & Svartvik, 1985; inter alia), and can

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be observed both in natural speech and well-edited texts like the *New York Times*. Production studies have established a well-attested and robust body of factors that affect the likelihood with which structurally-defined agreement fails and attraction is induced by a nearby element. These factors include the number features on potential attractors, their relative structural depth with respect to the grammatical controller, and linear order. (Bock & Cutting, 1992; Bock & Eberhard, 1993; Bock & Miller, 1991; Hartsuiker, Antón-Méndez, & Van Zee, 2001; Haskell & MacDonald, 2005; Thornton & MacDonald, 2003; Vigliocco and Nicol, 1998).

Accounts of agreement attraction have typically appealed to the notion that multiple nouns (or noun phrases) in a complex subject have independent specifications for number (Eberhard, 1997; Eberhard, Cutting, & Bock, 2005; Franck, Vigliocco, & Nicol, 2002; Hartsuiker et al., 2001; Solomon & Pearlmutter, 2004; Vigliocco & Nicol, 1998). The differences among these accounts lie in what allows grammatically illicit features to influence number valuation on the verb. There are two major proposals: (1) features spread erroneously in the noun phrase due to inherent properties of hierarchically structured representations; or (2) features of simultaneously activated constituents are confused in the planning of the verb form. A key difference between the two kinds of explanation for subject–verb agreement concerns the representation of the subject itself. On the first view, incorrect agreement is realized on the verb in production because the representation of the subject itself is internally inconsistent or faulty, due to properties of the combinatorial steps by which the representation is formed and maintained. On the second view, there is nothing inherently inconsistent or unreliable in how structure is represented over time, but only in how it is that distinct constituent representations are manipulated or accessed in language processing.

The current study examines agreement attraction in comprehension rather than production, bringing a different kind of evidence to bear on the debate. Data from seven experiments using both online and offline measures support the latter view of agreement attraction. In particular, we argue that agreement attraction in comprehension arises in the process of reaccessing information about the subject on the basis of cues at the verb, and not because the number of the subject is incorrectly represented. We present two related accounts of agreement attraction. In both, attraction reflects similarity-based interference that stems from cue-based retrieval (Lewis & Vasishth, 2005; McElree, Foraker, & Dyer, 2003).

Production

In the wake of Bock and Miller's seminal work (1991), numerous studies have established the parameters of agreement attraction in production. Most studies use an elicitation paradigm in which participants are presented with an auditory preamble constituting a subject phrase, like "The key to the cabinets", which they must repeat and finish. When the head noun is singular (i.e., *key*) and the embedded, or *local*, noun is plural (i.e., *cabinets*), there is a robust tendency for participants to use a verb form

with plural morphology, even though the subject phrase is itself singular. Across studies using simple count nouns, 13% of singular–plural preambles, on average, are continued with the plural verb form (Eberhard et al., 2005). It is crucial that the head noun be singular and the local noun plural, and not vice versa. Preambles like "The keys to the cabinet" lead to very few agreement errors (on average, 3%; Eberhard et al., 2005).

For the simplest case, i.e., $N_{SG}-P-N_{PL}-V$,² it has sometimes been suggested that the linear proximity of the plural noun, with respect to the verb, is responsible for attraction (e.g., Quirk et al., 1985). Indeed agreement attraction has sometimes been referred to as proximity concord (Francis, 1986; Quirk et al., 1985). Such an account is also consistent with contemporary models of comprehension in which parsing decisions are heavily influenced by local surface statistics (e.g., Tabor, Galantucci, & Richardson, 2004). However that view is undercut by the plural markedness effect, as well as by the existence of structural distance effects. Bock and Cutting (1992) and Solomon and Pearlmutter (2004) both show that local plurals embedded in a relative clause (e.g., "The editor who rejected the books") do not induce attraction as strongly as local plurals in a PP modifier. Vigliocco and Nicol (1998) demonstrate that linear adjacency is not a requirement for attraction, showing a similar proportion of subject–verb agreement errors when participants produce inverted yes/no questions like "Is/are the helicopter for the flights safe?" relative to declarative sentences in which the verb follows the subject. Franck et al. (2002) found that when the subject phrase contained two stacked PP modifiers like "The inscription(s) on the door(s) of the toilet(s)" the medial prepositional phrase led to more attraction errors than the most deeply embedded one. These results suggest that structural distance between a potential attractor and the subject head noun, or its syntactic projection, impacts the likelihood of attraction more so than its linear distance to the verb (although see Haskell & MacDonald, 2005, for arguments that small but measurable linear distance effects also exist).

Comprehension

In trying to understand the relation between agreement attraction and syntactic representation, evidence from agreement processing in comprehension provides a useful complement to evidence from production. Findings in comprehension are generally convergent with those from production: In the same scenarios in which individuals are likely to produce an agreement error, they experience less difficulty in processing an agreement error (Pearlmutter, Garnsey, & Bock, 1999). Whereas the key measure in production studies of agreement attraction is the proportion of agreement errors that an individual produces, the key measure in comprehension studies is typically either acceptability judgments (Clifton, Frazier, & Deevy, 1999; Häussler & Bader, 2009) or some index of processing diffi-

² The following standard linguistic category symbols are used throughout: N, noun; NP, noun phrase; P, preposition; PP, prepositional phrase; V, verb. RC stands for 'relative clause.' A category or word's grammatical number is indicated in subscript as either SG, singular, or PL, plural.

culty, as reflected in a localized reading time difference (e.g., Pearlmutter et al., 1999), or a signature pattern of evoked potentials (e.g., Kaan, 2002). A unique aspect of agreement studies in comprehension is in the ability to examine the response to both grammatical and ungrammatical agreement in agreement attraction environments.

Mechanisms

Based on the existence of hierarchical distance effects, previous authors working mainly in production have proposed that agreement attraction is a result of feature movement or ‘percolation’ within a syntactic representation (Eberhard et al., 2005; Franck et al., 2002; Nicol, Forster, & Veres, 1997; Vigliocco & Nicol, 1998). On this account, temporary structured representations are leaky enough that information is sometimes spuriously transmitted through the structural links between constituents. In percolation, features on a given syntactic constituent can be transferred to other, nearby constituents, but they can only be transferred one syntactic ‘step’ at a time; in other words, features must pass first to the immediately dominating syntactic node, then to the next, and so on. This ‘stepwise’ movement is reflected in the reduced likelihood of feature movement with increasing syntactic distance between nodes. In the typical agreement attraction case of a subject with a PP modifier (“the key to the cabinets”), the number features bound to the noun phrase within the PP percolate upward, valuing higher phrasal projections for number. In some proportion of cases, these features can percolate up to the highest projection, that of the subject noun phrase. By hypothesis, the verb or verb phrase is reliably valued by the number on the subject phrase, and so will be inappropriately valued in just that proportion of cases when the PP-object’s number percolates far enough to value the subject phrase.

The mechanism of feature percolation naturally accounts for structural depth effects like those demonstrated by Bock and Cutting (1992) and Franck et al. (2002); the most deeply embedded noun in a stack of PPs (like *toilets* in “the inscription on the door of the toilets”) or in a relative clause (like *books* in “the editor who rejected the books”) is uncontroversially more distant from the subject head noun than the noun in a single PP modifier (like *cabinets* in “the key to the cabinets”). Furthermore, feature percolation naturally encompasses the plural markedness effect if the feature system is privative (Trubetzkoy, 1939), i.e., singular number is represented by default in the absence of any number feature, whereas plural number is represented by the presence of plural feature (e.g., Eberhard, 1997; Kimball & Aissen, 1971). This implies that in the case of embedded singulars there should be no feature to percolate upwards, and therefore there should be no possibility for attraction to occur. In comprehension, feature percolation has been implemented through a ‘head overwriting’ mechanism in which the number feature on the head noun of the subject is ‘overwritten’ with the features of the attractor noun (Pearlmutter et al., 1999).

A related recent model of agreement processing also assumes that feature movement is responsible for agreement attraction effects, but generalizes the availability of move-

ment (Eberhard et al., 2005). Results from a Dutch study by Hartsuiker and colleagues showed that Subject_{SG}-Object_{PL}-Verb configurations can induce agreement attraction in production, although error rates were lower than is generally observed in PP-modifier constructions (Hartsuiker et al., 2001; although cf. Hemforth & Konieczny, 2003). Because the subject and object are not directly structurally related, a feature percolation model would have to assume that the intervening verb could take on the number features along the way. Instead, Eberhard and colleagues propose that the path for feature movement should be defined less rigidly than is the case in strict percolation approaches, and that any number information in a structure can spread to any other part of the structure in principle. However, it is unclear to what extent this model can capture the structural distance facts discussed above without assuming principles of feature movement very similar to those assumed by the strict percolation model.

The feature movement models discussed both share the property that they allow formation of a syntactic representation (here the subject) that is inconsistent with principles of the grammar. On the other hand, other models propose that agreement attraction effects arise primarily during the construction of the representation, and are more explicitly tied to the order in which constituents are planned (Badecker & Lewis, 2007; Bock & Cutting, 1992; Solomon & Pearlmutter, 2004). Solomon and Pearlmutter (2004) argue that attraction errors occur because features of both nouns are simultaneously activated in planning, with the distractor noun interfering with agreement processes before the subject representation is completed. Structural distance between the head and the attractor should correlate with the likelihood of errors because structural distance often reflects conceptual relatedness between the two, which in turn directly affects planning. Consistent with this, they show a correlation between agreement attraction in production and semantic relatedness when structural distance is held constant: More tightly related distractor nouns induce more agreement errors (e.g., “the pizza with the yummy toppings” vs. “the pizza with the tasty beverages”). In comprehension, this simultaneity of feature activation might be realized when a verb is encountered and its subject must be retrieved from among other noun phrases in memory to check the verb’s number features. The key point for this type of account is that the errors that arise do not stem from a faulty representation of the subject, but rather involve errors in mapping or retrieval in which multiple elements of the structure are simultaneously active.

Although there are formally well understood and well-motivated syntactic rules of percolation (Bayer & Johnson, 1995; Gazdar, Pullum, Klein, & Sag, 1985; Jackendoff, 1977; Shieber, 1986; van Riemsdijk & Williams, 1986), the explanations proposed in the agreement attraction literature imply a percolation mechanism that is importantly different, in that it allows agreement relationships to be formed that fail to follow grammatical constraints. There are at least two construals of the erroneous nature of this proposed mechanism: (1) errors reflect over-application of the regular feature percolation rules (Pearlmutter et al., 1999; Vigliocco & Nicol, 1998); or (2) errors result from

a rather more unconstrained system of feature spreading (Eberhard et al., 2005).

Under the first construal, the application of feature percolation is errorful because it sometimes ignores pertinent structural conditions. In grammatical systems percolation is constrained by structural notions like ‘head’: a syntactic projection is constrained to inherit certain features, like number or syntactic category, from its head (e.g., Pollard & Sag, 1994). In feature percolation accounts of agreement attraction, these features are inherited from either a non-head or the wrong head.

Under the second construal, the erroneous spread of features results from lower-level properties of the encoding architecture, such as spreading activation. Eberhard et al. (2005) in particular seem to have this construal in mind when they write:

When a source of number information is bound to a temporary structural network for an utterance, it transmits its information to the structure. Within the structure, the information moves or spreads according to principles of structural organization, assembly, and dissolution (p. 543)...Because SAP [*the model's continuously-valued number feature – WLP*] may flow unobstructed throughout a structural network, number information bound anywhere within a structure has the potential to influence agreement processes (p. 544).

In spreading activation models of combinatorial structure (e.g., Selman & Hirst, 1985; van der Velde & de Kamps, 2006; see Plate, 2003, for a comprehensive review), the potential for interaction between elements bound together in a structure generally implies the presence of connectivity between those elements. If feature percolation is akin to spreading activation, then positing the ‘unobstructed’ spread of features would also seem to require positing denser connectivity, since elements that the grammar does not typically relate, like the number feature of a complement and the maximal projection of its selecting head, must nonetheless influence one another. Thus, an encoding architecture that permits unconstrained feature spreading may actually be more resource intensive than one that does not.

The current study

In this study we examine the question of whether agreement attraction is due to instability in the representation of features on the subject, or rather to errors in accessing the subject representation or constructing the agreement dependency. We address this question in two different ways.

After validating the paradigm with Experiment 1, in Experiments 2 and 3 we consider an English construction that has been reported to induce attraction-like agreement patterns, but does not involve a complex subject. Kimball and Aissen (1971) report a pattern of acceptability in which sentences that contain a $N_{SG}-V_{PL}$ sequence within a singular-headed relative clause are uncontroversially reported as unacceptable (2a vs. 2b), but when the relative clause head noun is marked plural the acceptability of illicit $N_{SG}-V_{PL}$ sentences increases (3a vs. 3b). This configura-

tion thus exhibits a plural markedness effect similar to the complex subject case of agreement attraction: acceptability of subject–verb agreement is not impacted by the number of a nearby noun when the subject is plural, but only when it is singular.

- (2)
- (a) The driver_{SG} who the runner_{SG} waves_{SG} to each morning honks back cheerfully.
 - (b) *The driver_{SG} who the runner_{SG} wave_{PL} to each morning honks back cheerfully.
- (3)
- (a) The drivers_{PL} who the runner_{SG} waves_{SG} to each morning honk back cheerfully.
 - (b) ?The drivers_{PL} who the runner_{SG} wave_{PL} to each morning honk back cheerfully.

Kimball and Aissen’s study was observational (and they attributed the pattern to a Northeast US/Boston dialect), but recent experimental work using cumulative acceptability judgments supports the original judgments (Clifton et al., 1999). These configurations have been shown to induce attraction effects in production (Bock & Miller, 1991; Franck, Lassi, Frauenfelder, & Rizzi, 2006), and we have also found these types of errors in well-edited texts (4). However, to date attraction in this construction has not been examined in comprehension, and has not been systematically compared with attraction in the more well-studied prepositional-modifier cases.

- (4)
- (a) We can live with the [_{NP} errors_{PL}] [_{RC} that **classification software**_{SG} make_{PL} ...] (Nunberg, 2003, p. 5).
 - (b) These include ... the [_{NP} problems_{PL}] [_{RC} that **incrementality**_{SG} pose_{PL} ...] (Byram, 2007, p. 58).

On a percolation account, such constructions should not induce strong attraction effects. The hierarchical relation between the agreeing subject and the attractor is inverted, in comparison to the PP cases. Firstly, traditional percolation mechanisms are specified for percolation ‘upward’ through a tree only, and thus do not predict that features can also travel ‘downward’, as they would have to in this case. Secondly, even if downward percolation were also allowed, the probability that the features of the attractor could percolate through the numerous intervening nodes to reach the subject should be fairly low, and certainly lower than in the PP-modifier case. Furthermore, the attractor does not linearly intervene between the subject and the verb, so the features of the attractor should presumably be less activated relative to those of the head noun. Thus, finding attraction effects of comparable size to the PP-modifier case would provide evidence against classic percolation models of agreement attraction.

In Experiments 4–7 we focus on a prediction not just of percolation models, but any account that assumes that errors result from incorrect representation of the subject. The prediction is that the reduced disruption due to agreement attraction in the comprehension of ungrammatical sen-

tences should be mirrored by an increased disruption of approximately the same size due to agreement attraction in grammatical sentences. On such accounts, agreement attraction in comprehension is due to the fact that in some proportion of trials, simple $N_{SG}-P-NP_{PL}$ subjects are incorrectly valued as plural ($[N_{SG}[P-NP_{PL}]]_{PL}$) through percolation or some other mechanism, before the verb is ever encountered. Whenever this happens, $N_{SG}-P-NP_{PL}-V_{PL}$ sequences should be considered grammatical, and importantly, $N_{SG}-P-NP_{PL}-V_{SG}$ sequences should be considered *ungrammatical*. Therefore, on such accounts, the rate of errors in grammatical and ungrammatical sentences should be tightly linked.

The existing data relevant to this prediction of attraction symmetry in grammatical and ungrammatical sentences is somewhat mixed. Nicol et al. (1997) showed that offline responses were slower in grammatical sentences with a PP-internal plural attractor (*The key to the cabinets is...*) than in sentences with a singular attractor, and Pearlmutter et al. (1999) provide evidence from eye-tracking and self-paced reading that in grammatical sequences, PP-internal plural attractors lead to greater processing difficulty in the verb region. However, when ungrammatical and grammatical cases have been included in the same experiment (e.g., Experiments 1 and 2 in Pearlmutter et al., 1999), the timing and duration of attraction effects are significantly different between the two cases, which is unexpected on the percolation account. More importantly, comparing grammatical, singular-attractor sentences and grammatical, plural-attractor sentences is potentially confounded by the additional processing load that may be incurred by adding a plural attractor NP to the sentence. Plurals are morphologically and arguably conceptually more complex than singulars, and semantically composing plurals with other predicates in the sentence may also be more costly. Noun number is well known to affect lexical decision times (Lau, Rozanova, & Phillips, 2007; Lehtonen, Wande, Niska, Niemi, & Laine, 2006; New, Brysbaert, Segui, Ferrand, & Rastle, 2004). When the plural cost and the attraction effect go in opposite directions, as in ungrammatical attraction cases where the attractor improves the sentence, there is no danger of one being mistaken for the other; the danger arises when the potential effects go in the same direction, as in grammatical sentences. This is particularly problematic for online experiments in which the attractor region is immediately adjacent to the verb, as the strongest effects of plural processing complexity would likely be felt here.

In five experiments (Experiments 2–6) we revisit the prediction of attraction symmetry in ungrammatical and grammatical contexts by comparing the effect of attractor number on reading times for ungrammatical and grammatical sentences in both the traditional PP-modifier attraction constructions as well as the relative clause constructions discussed above, in which the plural attractor region is well separated from the critical verb position. A finding of ‘grammatical asymmetry’ in which attraction effects disappear in grammatical sentences would be problematic for any model that assumes that it is the faulty representation of the subject noun phrase itself that is responsible for attraction in comprehension.

Note that although we describe the results separately for ease of presentation, with the exception of Experiment 1, a test session always included materials from both a relative-clause manipulation and a prepositional modifier manipulation. In particular, the materials from Experiments 3 and 5 were tested in the same session and the materials from Experiments 2 and 6 were tested in the same session.

Experiment 1

Previous behavioral studies of agreement in comprehension have rarely tested the strength of the ungrammaticality effect in the baseline case, that is, when subject and verb mismatch in number and no attractor NP is present. The goal of Experiment 1 was to determine the size and time course of the ungrammaticality effect in self-paced reading for this baseline case. This experiment also provided an opportunity to test whether the additional complexity due to processing a plural would in itself have an effect on self-paced reading times. Finally, the contrast between singular and plural subject–verb mismatch in the no-attractor case is also of some interest, given that sentences with singular and plural subjects are differentially sensitive to attraction effects.

Participants

Participants were 32 native speakers of English from the University of Maryland community with no history of language disorders. All participants in this and following experiments provided informed consent. Participants were either compensated \$10/h or received credit in an introductory Linguistics class. No participant took part in more than one experimental session.

Materials

Materials for all experiments are presented in Appendix A. Experimental materials consisted of 24 sentence sets arranged in a 2×2 design with subject number (singular/plural) and grammaticality (grammatical/ungrammatical) as factors. Sixteen sentence sets were derived from the materials of Pearlmutter et al. (1999), with attractor nouns removed, and eight further sentence sets were created for this study. An example set is presented in Table 1. The first five words of each experimental item always followed the same form: *determiner-adjective-noun-adverb-verb*. The verb was always either auxiliary or copular ‘be’. Since singular and plural subjects differ both in the number of characters and morphological complexity, an adverb was included to make it easier to distinguish any effects due to the noun from effects caused by the verb itself. The word following the critical verb was either an adjective or past participle and never carried agreement. The 24 sets of four conditions were distributed across four lists in a Latin Square design, and combined with 84 grammatical filler sentences of similar length (48 of these fillers consisted of two separate manipulations unrelated to agreement processing which are not presented here). This resulted in 11% of the items being ungrammatical.

Table 1

Sample set of experimental items for Experiment 1.

Singular subject/grammatical	The old key unsurprisingly was rusty from many years of disuse...
Plural subject/grammatical	The old keys unsurprisingly were rusty from many years of disuse...
Singular subject/ungrammatical	The old key unsurprisingly were rusty from many years of disuse...
Plural subject/ungrammatical	The old keys unsurprisingly was rusty from many years of disuse...

Procedure

Sentences were presented on a desktop PC using the Linger software (Doug Rohde, MIT) in a self-paced word-by-word moving window paradigm (Just, Carpenter, & Woolley, 1982). Each trial began with a screen presenting a sentence in which the words were masked by dashes while spaces and punctuation remained intact. Each time the participant pressed the space bar, a word was revealed and the previous word was re-masked. A yes/no comprehension question appeared all at once on the screen after each sentence. The 'f' key was used for 'yes' and the 'j' key was used for 'no'. Onscreen feedback was provided for incorrect answers. Participants were instructed to read at a natural pace and answer the questions as accurately as possible. In all of the self-paced reading experiments presented here, participants were never informed that sentences would contain grammaticality errors. Order of presentation was randomized for each participant. Seven practice items were presented before the beginning of the experiment.

Analysis

Only items for which the comprehension question was answered correctly were included in the analysis. Reading times that exceeded a threshold of 2.5 standard deviations, by region and condition, were excluded (Ratcliff, 1993). Across all self-paced reading experiments reported in this paper, on average by region this standard deviation trim resulted in the exclusion of 2.6% of correctly-answered trials (min: 2.3%, max: 3.1%). The regions used for analysis consisted of single words. Data for each of the first 10 regions of the sentence were entered into a 2×2 repeated-measures ANOVA with subject number and grammaticality as factors. Using R (R Development Core Team, Vienna), ANOVAs were computed on participant mean reading times across items (F_1) and on item means across participants (F_2). $\text{Min}P$ statistics (Clark, 1973; Raaijmakers, Schrijnemakers, & Gremmen, 1999) were also computed, although because our items were counterbalanced across lists, this test is probably too conservative (see Raaijmakers et al., 1999 for discussion). ANOVA statistics for regions of interest are presented in Table 2: these were the subject region (R3), the adverb region (R4), the critical verb region (R5), and the four regions following the critical verb (R6–10). We performed a complementary analysis by fitting linear mixed-effect models to our data, simultaneously controlling for subject and item as random factors. Models were fit using restricted log-likelihood maximization and 95% confidence intervals (CIs) were then derived from these models by Markov Chain Monte Carlo simulation

(Baayen, Davidson, & Bates, 2008). These are presented in the text.

Results

Comprehension question accuracy

The mean comprehension question accuracy for experimental items across participants and items was 96.7%, and did not differ across conditions (logistic mixed-effects model, ps n.s.). For singular subjects, grammatical sentences were answered with an accuracy of $95.3 \pm 1.7\%$ and ungrammatical sentences with an accuracy of $96.9 \pm 1.4\%$ (standard error is computed across participant means). For plural subjects, grammatical accuracy was $95.8 \pm 1.5\%$ and ungrammatical accuracy was $99.0 \pm 0.7\%$.

Self-paced reading

The results from Experiment 1 are presented in Fig. 1. The subject region (R3) showed no significant differences ($F_s < 1$). However, the subsequent adverb region (R4) showed a main effect of number, such that the plural conditions had longer reading times (plural mean = 480 ms; singular mean = 417 ms; 95% CI = 23 ms; $p < .001$).

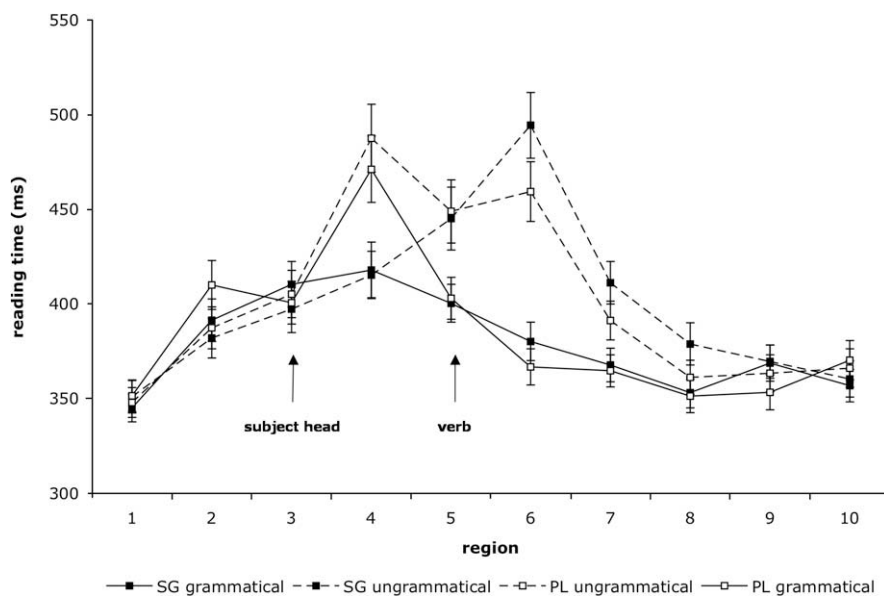
The critical verb region (R5) showed a main effect of grammaticality (grammatical mean = 402 ms; ungrammatical mean = 447 ms; 95% CI = 23 ms; $p < .01$), no significant effect of number and no interaction ($F_s < 1$). This grammaticality effect persisted into Regions 6–8, and was largest in the immediate post-verbal region (R6) (grammatical mean = 374 ms; ungrammatical mean = 477 ms; 95% CI = 18 ms; $p < .0005$). Although the singular-subject ungrammatical condition showed somewhat longer reading times than the plural-subject ungrammatical condition in the immediate post-verbal region (R6), the interaction was non-significant. In a pooled analysis of the three immediate post-verbal regions (R6–8), the coefficient of the grammaticality: number treatment effect did approach marginal significance (-17 ms; 95% CI $[-38$ ms, 6 ms]; $p < .15$).

Discussion

The main effect of number that we found in the region immediately following the subject head noun suggests that some aspect of reading the plural noun does exact a significant reading time cost on the following region. This plural cost could be due to morphological processing, conceptual processing, semantic integration, or even length per se (e.g., the additional character could cause fixations to be less optimally positioned). The current data do not allow us to discriminate between these possible explanations, which make different predictions about the duration of

Table 2Experiment 1: Omnibus repeated measures analysis of variance. ANOVA tests reliable at $\alpha = 0.05$ highlighted in bold.

	By participants				By items				MinF'			
	df	MS _{effect}	F ₁	p	df	MS _{effect}	F ₂	p	df	minF'	p	
<i>Region 3 (subject)</i>												
Grammaticality	1,31	3724	0.18	.67	1,23	4105	0.15	.70	1,51	0.08	.78	
Subject number	1,31	216	0.01	.92	1,23	446	0.01	.92	1,53	0.01	.92	
Number × gram.	1,31	14,652	0.83	.37	1,23	21,556	0.91	.35	1,53	0.43	.51	
<i>Region 4 (adverb)</i>												
Grammaticality	1,31	16,047	0.64	.43	1,23	9537	0.14	.72	1,33	0.11	.74	
Subject number	1,31	664,627	14.5	<.001	1,23	689,556	9.34	.01	1,48	5.68	.02	
Number × gram.	1,31	18,589	0.65	.43	1,23	18,982	0.47	.50	1,49	0.27	.61	
<i>Region 5 (verb)</i>												
Grammaticality	1,31	376,432	8.97	.01	1,23	353,467	6.94	.01	1,50	3.91	.05	
Subject number	1,31	2595	0.09	.77	1,23	3312	0.14	.71	1,54	0.05	.82	
Number × gram.	1,31	617	0.02	.88	1,23	256	0.01	.91	1,43	0.01	.92	
<i>Region 6 (verb + 1)</i>												
Grammaticality	1,31	1,922,696	59.2	<.001	1,23	1,957,355	50.3	<.001	1,51	27.2	<.001	
Subject number	1,31	101,120	3.77	.06	1,23	112,310	4.15	.05	1,53	1.97	.17	
Number × gram.	1,31	27,296	0.74	.4	1,23	21,992	0.48	.49	1,48	0.29	.59	
<i>Region 7 (verb + 2)</i>												
Grammaticality	1,31	210,563	16.4	<.001	1,23	221,568	7.47	.01	1,42	5.14	.03	
Subject number	1,31	25,372	2.72	.11	1,23	20,459	1.50	.23	1,45	0.97	.33	
Number × gram.	1,31	9116	0.68	.42	1,23	10,458	0.84	.37	1,54	0.38	.54	
<i>Region 8 (verb + 3)</i>												
Grammaticality	1,31	50,907	5.37	.03	1,23	58,906	4.07	.06	1,50	2.32	.13	
Subject number	1,31	23,238	2.06	.16	1,23	16,298	1.00	.33	1,43	0.67	.42	
Number × gram.	1,31	8670	0.92	.35	1,23	11,122	1.15	.29	1,54	0.51	.48	
<i>Region 9 (verb + 4)</i>												
Grammaticality	1,31	7005	0.87	.36	1,23	5772	0.36	.56	1,41	0.25	.62	
Subject number	1,31	20,268	2.31	.14	1,23	16,710	0.83	.37	1,39	0.61	.44	
Number × gram.	1,31	4617	0.53	.47	1,23	3756	0.36	.55	1,48	0.22	.64	

**Fig. 1.** Experiment 1: Self-paced reading results. Region by region means according to subject number and grammaticality. Error bars indicate standard error of the mean. *Sample sentence:* The₁ old₂ key(s)₃ unsurprisingly₄ was/were₅ rusty₆ from₇ many₈ years₉ of₁₀ . . .

the effect and the extent to which the effect should be observed for nouns in other positions in the sentence.

Because number and grammaticality manipulations occur nearby in sentences used in agreement attraction experiments, these results suggest that some care must

be taken in deciding whether reading time increases should be attributed to factors associated with processing nominal number alone or to factors associated with licensing an agreement relation. In the case of the simple sentences in Experiment 1, the inclusion of the adverb

allowed us to see that effects of noun number preceded the critical verbal region. However, the effect of number was larger than plural effects that we have found previously (Lau et al., 2007), perhaps related to the longer reading times and increased variability in reaction times observed, or perhaps because the critical noun appeared early in the sentence.

The main effect of grammaticality in the critical verb region shows that grammaticality effects can be found on the critical region itself in a self-paced reading paradigm, and that the differential sensitivity of singular and plural subjects to attractors is not a function of differential initial sensitivity to subject–verb agreement errors in the baseline no-attractor case. The main effect of grammaticality at the critical region for these no-attractor cases was 45 ms (control s.d.: 137 ms; Cohen's $d = 0.33$). The lack of a reading time difference between the two ungrammatical conditions at the verb also suggests that the form of the verb ('was'/'were') does not have a significant effect on reaction times. Interestingly, singular subjects led to a consistently larger deflection in reading times for ungrammatical conditions in later regions, but this effect was not reliable.

Experiment 2

Experiment 2 was designed to test the online effects of agreement attraction in object relative clause constructions, in which the relative clause head is a potential attractor with respect to the agreement between the relative clause subject and verb. This configuration is doubly interesting. Firstly, the plural relative clause head does not intervene, either linearly or hierarchically, between the subject and the verb. Finding agreement attraction in this configuration would present a challenge for straightforward feature percolation accounts, as the dominance path that connects the relative clause head and the relative clause subject runs opposite to that found in PP constructions and requires both upwards and downwards percolation. Secondly, in this construction the local environment immediately preceding the verb is identical regardless of the number on the potential attractor, meaning that the comparison of grammatical cases is less susceptible to plural complexity effects.

Because previous literature in both comprehension and production has shown that singular subject/plural attractor configurations demonstrate much larger and more reli-

able effects than plural subject/singular attractor configurations (Eberhard, 1997; Pearlmutter et al., 1999; cf. Pearlmutter, 2000), we tested only singular subject cases, where the attractor could be either singular or plural. If this configuration is subject to attraction effects, we should see differences between plural attractor cases, in which the attractor differed in number from the subject, and singular attractor cases, in which the number on both nouns was the same.

Participants

Participants were 30 native speakers of English from the University of Maryland community with no history of language disorders.

Materials

Experimental materials consisted of 48 sentence sets arranged in a 2×2 design with relative clause head number (singular/plural) and grammaticality (grammatical/ungrammatical) as factors. An example set is presented in Table 3. The first six words always contained a noun phrase modified by a relative clause, following the template *determiner-noun-'who'-determiner-noun-verb*. The agreement relation manipulated here was the agreement between the subject noun and verb inside the relative clause, and thus the head noun modified by the relative clause was considered the 'attractor'. The subject of the relative clause was always singular. In this design the noun immediately adjacent to the verb was always singular, such that effects on the verb were less likely to be conflated with effects of noun number per se. The word following the critical verb was usually a short function word and never carried agreement. The 48 sentence sets were distributed across four lists in a Latin Square design, and were combined with 24 items of a prepositional-phrase agreement attraction design (all grammatical; data presented below as Experiment 6) and 144 filler sentences of similar length. This resulted in 17% of the items being ungrammatical.

Procedure and analysis

The same self-paced reading procedure was used as in Experiment 1. The analysis followed the same steps. Only items for which the comprehension question was an-

Table 3

Sample set of experimental items for Experiments 2 and 3.

Singular subject items (Experiments 2 and 3)

Singular attractor/grammatical
Plural attractor/grammatical
Singular attractor/ungrammatical
Plural attractor/ungrammatical

The musician who the reviewer praises so highly will probably win a Grammy
The musicians who the reviewer praises so highly will...
The musician who the reviewer praise so highly will...
The musicians who the reviewer praise so highly will...

Plural subject items (Experiment 3)

Singular attractor/grammatical
Plural attractor/grammatical
Singular attractor/ungrammatical
Plural attractor/ungrammatical

The musician who the reviewers praise so highly will...
The musicians who the reviewers praise so highly will...
The musician who the reviewers praises so highly will...
The musicians who the reviewers praises so highly will...

swered correctly were included in the analysis. Reading times that exceeded a threshold of 2.5 s.d. by region and condition were excluded. Two participants showed a comprehension question accuracy rate of less than 80% across all items and were thus excluded from further analysis.

The regions used for analysis consisted of single words. Data for each of the first 10 regions of the sentence were entered into a 2×2 repeated-measures ANOVA with attractor number and grammaticality as factors. Regions of interest were 2–9; the attractor noun appeared in Region 2, the subject noun appeared in Region 5, and the critical verb appeared in Region 6. Statistics for each of these nine regions are presented in Table 4.

Results

Comprehension question accuracy

The mean comprehension question accuracy for experimental items across participants and items was 92.3%, and did not differ across conditions (logistic mixed-effects mod-

el, all *ps* n.s.). For singular RC head conditions, accuracy in the grammatical condition was $94.3 \pm 1.6\%$ and in the ungrammatical condition $91.7 \pm 1.8\%$. For plural RC heads, accuracy in the grammatical condition was $93.2 \pm 1.5\%$ and in the ungrammatical condition $90.2 \pm 2.2\%$.

Self-paced reading

As shown in Fig. 2, Region 2 (the attractor) showed a main effect of attractor number, such that the plural conditions had longer reading times (plural mean = 322; singular mean = 311; 95% CI = 7.7 ms, $p < .05$). Since the verb was not encountered until Region 6, this effect was likely driven by additional processing costs associated with plural nouns relative to singular ones. Longer reading times for the plural-attractor conditions persisted to the critical verb (R6); the main effect was reliable at the relative pronoun (R3) and the relative clause subject noun (R5).

The critical verb region (R6) did not show a main effect of grammaticality ($F_s < 1$). However, the region following the verb (R7) showed main effects of attractor number

Table 4

Experiment 2: Omnibus repeated measures analysis of variance. ANOVA tests reliable at $\alpha = 0.05$ highlighted in bold.

	By participants				By items				Min F		
	<i>df</i>	<i>MS</i> _{effect}	<i>F</i> ₁	<i>p</i>	<i>df</i>	<i>MS</i> _{effect}	<i>F</i> ₂	<i>p</i>	<i>df</i>	min F	<i>P</i>
<i>Region 2 (RC head)</i>											
Attractor number	1,27	3642	5.7	.02	1,47	7715	2.84	.09	1,74	1.89	.17
Grammaticality	1,27	1866	1.68	.21	1,47	3506	2.15	.14	1,63	0.94	.34
Number \times gram.	1,27	307	0.5	.49	1,47	4547	2.42	.12	1,38	0.41	.53
<i>Region 3 ('who')</i>											
Attractor number	1,27	4109	6.49	.02	1,47	5004	1.97	.16	1,69	1.51	.22
Grammaticality	1,27	704.1	1.23	.28	1,47	397	0.25	.62	1,64	0.21	.65
Number \times gram.	1,27	1471	1.56	.22	1,47	2914	1.87	.17	1,65	0.85	.36
<i>Region 4 ('the')</i>											
Attractor number	1,27	400	1.75	.20	1,47	1058	0.79	.38	1,73	0.54	.46
Grammaticality	1,27	977	2.31	.14	1,47	284	0.29	.59	1,58	0.25	.62
Number \times gram.	1,27	187	0.22	.64	1,47	243	0.13	.72	1,74	<0.1	.78
<i>Region 5 (RC subject)</i>											
Attractor number	1,27	4001	6.26	.02	1,47	10,474	4.8	.03	1,73	2.71	.1
Grammaticality	1,27	282	0.61	.44	1,47	11	<0.1	.94	1,48	<0.1	.92
Number \times gram.	1,27	51	<0.1	.81	1,47	1020	0.51	.47	1,33	<0.1	.82
<i>Region 6 (verb)</i>											
Attractor number	1,27	3051	2.06	.16	1,47	7341	2.04	.15	1,69	1.02	.32
Grammaticality	1,27	270	0.33	.57	1,47	335	<0.1	.78	1,66	<0.1	.79
Number \times gram.	1,27	2722	0.32	.58	1,47	321	0.12	.73	1,71	<0.1	.77
<i>Region 7 (verb + 1)</i>											
Attractor number	1,27	28,444	8.24	.01	1,47	49,733	12.2	<.01	1,60	4.91	.03
Grammaticality	1,27	38,706	5.31	.03	1,47	56,498	9.87	<.01	1,55	3.45	.07
Number \times gram.	1,27	17,078	6.92	.01	1,47	31,842	10.6	<.01	1,59	4.18	.05
<i>Region 8 (verb + 2)</i>											
Attractor number	1,27	2846	2.37	.14	1,47	4518	1.09	.30	1,73	0.75	.39
Grammaticality	1,27	3312	1.97	.17	1,47	4587	1.32	.25	1,74	0.79	.38
Number \times gram.	1,27	869	1.27	.27	1,47	1102	0.3	.58	1,66	0.24	.63
<i>Region 9 (verb + 3)</i>											
Attractor number	1,27	3845	4.26	.05	1,47	7502	4.24	.04	1,69	2.12	.15
Grammaticality	1,27	0.6	<0.1	.98	1,47	490	0.1	.75	1,27	<0.1	1
Number \times gram.	1,27	590	0.88	.36	1,47	1264	0.91	.34	1,68	0.45	.5
<i>Region 10 (verb + 4)</i>											
Attractor number	1,27	4451	3.75	.06	1,47	7104	3.8	.05	1,68	1.89	.17
Grammaticality	1,27	5062	3.3	.08	1,47	11,269	5.91	.02	1,56	2.12	.15
Number \times gram.	1,27	188	0.227	.64	1,47	1198	0.503	.48	1,51	0.16	.69

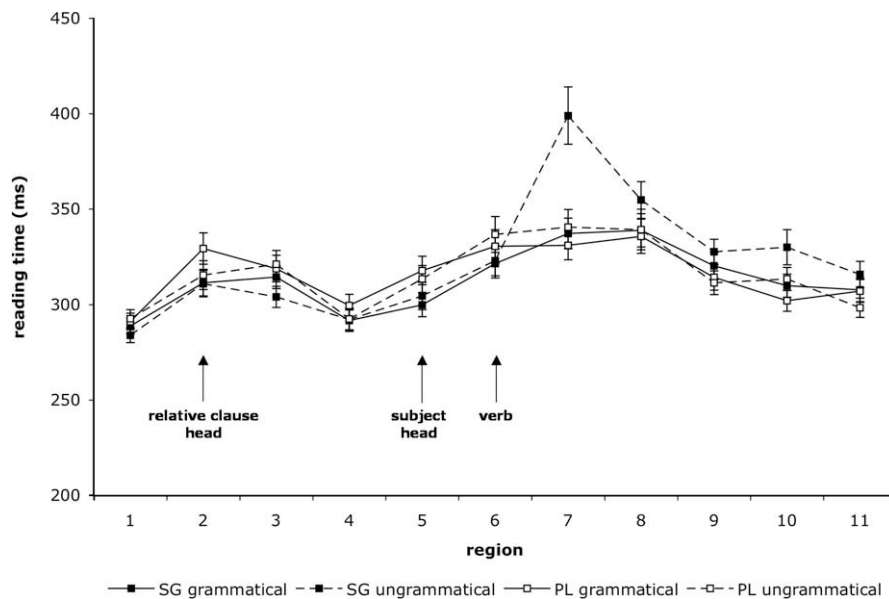


Fig. 2. Experiment 2: Self-paced reading results. Region by region means segregated by relative clause head number and grammaticality. Error bars indicate standard error of the mean. *Sample sentence:* The₁ musician(s)₂ who₃ the₄ reviewer₅ praise(s)₆ so₇ highly₈ will₉ probably₁₀ win(s)₁₁...

and grammaticality, and crucially, an interaction between grammaticality and attractor number. Pairwise comparisons in Region 7 showed a significant grammaticality effect only when the relative clause head was singular (grammatical mean = 337 ms; ungrammatical mean = 399 ms; 95% CI = 27.2 ms, $p < .05$), but not when it was plural (grammatical mean = 331; ungrammatical mean = 341; 95% CI = 18.7 ms, $p > .1$). No significant effects were found in Region 8, but in Regions 9 and 10 the main effect of attractor number again was significant, as well as the effect of grammaticality in Region 10 (significant by participants, marginal by items).

Several previous studies have reported that the presence of an attractor not only reduces disruption to subject–verb mismatches when the attractor matches the verb, but also causes disruption in grammatical subject–verb match sentences when the attractor mismatches the verb. To investigate this possibility in our relative clause materials we conducted a pairwise comparison over the two grammatical conditions in the first post-verbal region (7), where we found the attraction effect in the ungrammatical cases. No significant differences were found (singular attractor mean = 337 ms; plural attractor mean = 331 ms; 95% CI = 16.3 ms; $p > .1$).

Discussion

The results of Experiment 2 suggest that the head of a relative clause can act as a strong attractor for agreement. When the RC head and the subject were both singular, the region following the critical verb showed significantly longer reading times in the ungrammatical condition, where the verb was plural, than in the grammatical condition, where the verb was singular. However, when the RC head was plural, the ungrammatical singular subject–plural verb combination did not differ from the grammatical

singular subject–singular verb condition in the region following the verb. Thus, we found that for subjects within RCs, an RC head attractor matching the RC verb's number significantly reduced the reading time disruption normally seen to subject–verb number mismatch. A similar reduction in the reading time disruption has previously been observed for agreement attraction caused by subject-attached PPs (Pearlmutter et al., 1999).

These results contrast with the predictions of a standard percolation account. Such accounts would predict that because the RC head noun hierarchically commands the RC subject, it should exert no attraction effect whatsoever. These data also contrast with a more liberal version of percolation, in which downwards feature percolation is also permitted. Under the assumption that the structural distance between two nodes determines the likelihood that features will spread from one node to the other, then RC attraction should be relatively weaker than in the PP-modifier case given the greater structural distance between the RC head noun and the RC subject. In fact, the attraction effect was as strong as possible, in the sense that the disruption due to ungrammaticality was eliminated entirely. One alternative explanation for this pattern is that, because of the increased processing demands of a relative clause structure, it is hard for the reader to notice ungrammaticality even in the baseline case. However, we found that the ungrammatical condition in which neither noun matched the verb's number showed a slow-down of 62 ms in the region following the critical verb (pooled s.d.: 201 ms; Cohen's d : 0.31), relative to the corresponding grammatical condition in which both nouns matched the verb. Both the absolute and normalized mean differences were comparable to the grammaticality effect observed in Experiment 1, despite significant differences in verb type (copula/auxiliary vs. main verb) and in experiment-wide

reading times. Thus subject–verb mismatch seems equally disruptive whether it occurs in the main clause or within a relative clause.

We also found that there was no attractor effect in the grammatical conditions. In contrast to the PP-modifier configuration, in which the attractor is adjacent to the verb, the attractor was non-intervening in the RC configuration. Consequently the material adjacent to the verb was identical across singular and plural-attractor conditions resulting in a better-matched baseline prior to the verb. We found that in these RC configurations the grammatical plural-attractor condition did not show significantly longer reading times than the grammatical singular attractor condition.

Experiment 3

The results of Experiment 2 showed that the presence of a plural RC-head reduced the disruption due to mismatch between a singular RC-subject and a plural RC-verb. This appears similar to previous findings of attraction effects in prepositional constructions (*The key to the cabinets are...*) in both comprehension and production. However, since the order of attractor and subject was reversed, it is conceivable that our effect represents a different process. To provide a further test of whether these phenomena represent the same underlying process, Experiment 3 tested for another property of the attraction effect found in prepositional constructions, namely the singular–plural asymmetry. Previous work has shown strong attraction effects for singular-subject/plural-attractor pairs, but not for the corresponding plural-subject/singular-attractor pairs (Pearlmutter et al., 1999). Finding the same asymmetry for the RC construction would strengthen the evidence that the attraction observed in RC structures has the same cause as classic attraction effects.

Participants

Participants were 60 native speakers of English from the University of Maryland community with no history of language disorders.

Materials

Experimental materials consisted of the same 48 sentence sets as in Experiment 2, but this time arranged in a $2 \times 2 \times 2$ design with attractor number (singular/plural), subject number (singular/plural), and grammaticality (grammatical/ungrammatical) as factors. Although in this design the noun immediately adjacent to the verb could be singular or plural, the comparisons of interest were between conditions in which the subject number was matched, and therefore effects of noun number were less of a concern. However, in an effort to minimize such effects the subject nouns were chosen such that on average across items they occurred equally frequently in the singular or the plural, since infrequent plural forms have been shown to have a greater effect on reading times than frequent ones (e.g., New et al., 2004; see Bock, Eberhard, & Cutting, 2004 for relevant effects in production).

Counts were derived from the Cobuild Bank of English corpus (320 million words). The word following the critical verb was usually a short function word and never carried agreement. The 48 sentence sets were distributed across eight lists in a Latin Square design, and were combined with 24 items of a prepositional-phrase agreement attraction design (half ungrammatical; data presented below as Experiment 5) and 216 filler sentences of similar length. This resulted in 13% of the items being ungrammatical.

Procedure and analysis

The procedure was the same self-paced reading procedure described in Experiment 1, and the analysis followed similar steps. Only items for which the comprehension question was answered correctly were included in the analysis. Reading times that exceeded a threshold of 2.5 s.d. by region and condition were excluded. Due to experimenter error, the distribution of participants across the eight lists was unbalanced. In the analysis presented here, a subset of 56 participants was analyzed such that participants were evenly balanced across the lists; however, the pattern of results did not differ from the analysis in which all 60 participants were included.

The regions used for analysis consisted of single words. Data for the first ten regions of the sentence were examined; the critical verb appeared in Region 6. In this experiment, the comparisons of interest were all within a level of the subject number factor: we were interested in whether the four plural-subject conditions would show the same pattern relative to each other as the four singular-subject conditions. In order to examine this question we split the design into two 2×2 repeated-measures ANOVAs, one for each level of subject number (singular/plural), with attractor number and grammaticality as factors. For completeness, we also computed a $2 \times 2 \times 2$ repeated-measures ANOVA with attractor number, subject number, and grammaticality as factors. Regions of interest were 2 (attractor), 3, 5 (relative clause subject), 6 (verb), 7, and 8; statistics for these regions are presented in Tables 5 and 6.

Results

Comprehension question accuracy

The mean comprehension question accuracy for experimental items across participants and items was 93.7%, and did not differ reliably across experimental conditions. For sentences with a singular RC subject and a singular RC head, accuracy in the grammatical condition was $93.3 \pm 1.4\%$ and in the ungrammatical condition $96.4 \pm 1.1\%$. For sentences with a singular RC subject and a plural RC head, accuracy in the grammatical condition was $94.4 \pm 1.3\%$ and in the ungrammatical condition $94.7 \pm 1.3\%$. For sentences with a plural RC subject and a singular RC head, accuracy in the grammatical condition was $94.4 \pm 1.3\%$ and in the ungrammatical condition $93.6 \pm 1.3\%$. For sentences with a plural RC subject and a plural RC head, accuracy in the grammatical condition was $91.7 \pm 1.7\%$ and in the ungrammatical condition $91.7 \pm 1.3\%$.

Table 5

Experiment 3: Omnibus repeated measures analysis of variance. ANOVA tests reliable at $\alpha = 0.05$ highlighted in bold.

	By participants				By items				MinF'		
	df	MS _{effect}	F ₁	p	df	MS _{effect}	F ₂	p	df	minF'	p
<i>Region 2 (Rhead)</i>											
Grammaticality	1,55	643	0.35	.56	1,47	2416	2.08	.16	1,73	0.3	.59
Attractor number	1,55	20,084	8.18	.01	1,47	14,098	5.89	.02	1,96	3.42	.07
Subject number	1,55	2643	1.43	.24	1,47	4792	2.05	.16	1,101	0.84	.36
Att-Num × gram.	1,55	9320	2.52	.12	1,47	3402	1.05	.31	1,82	0.74	.39
Sub-Num × gram	1,55	711	0.39	.59	1,47	580	0.26	.62	1,100	0.14	.71
A-num × S-num	1,55	9320	2.52	.12	1,47	6379	2.36	.13	1,101	1.22	.27
3-Way interaction	1,55	1042	0.53	.47	1,47	353	0.15	.70	1,72	0.12	.73
<i>Region 3 ('who')</i>											
Grammaticality	1,55	314	0.29	.59	1,47	75	<0.1	.84	1,102	0.91	.34
Attractor number	1,55	8909	5.52	.02	1,47	5052	3.6	.06	1,94	2.18	.14
Subject number	1,55	2212	1.26	.27	1,47	7988	4.22	.05	1,84	0.97	.33
Att-Num × gram.	1,55	2	<0.1	.97	1,47	18	<0.1	.93	1,78	<0.1	1
Sub-Num × gram	1,55	152	<0.1	.76	1,47	570	0.47	.5	1,75	<0.1	.78
A-num × S-num	1,55	1876	1.01	.32	1,47	1854	1.9	.18	1,97	0.66	.42
3-Way interaction	1,55	4427	4.03	.05	1,47	3437	1.93	.17	1,86	1.3	.26
<i>Region 5 (RC subj)</i>											
Grammaticality	1,55	703	0.27	.60	1,47	2749	1	.32	1,82	0.21	.65
Attractor number	1,55	15,895	7.03	.01	1,47	10,596	4.75	.03	1,95	2.83	.1
Subject number	1,55	8661	4.34	.04	1,47	9244	5.35	.03	1,102	2.4	.12
Att-Num × gram.	1,55	828	0.39	.54	1,47	3723	1.02	.32	1,90	0.28	.6
Sub-Num × gram	1,55	1945	0.76	.39	1,47	2940	1.36	.25	1,98	0.49	.49
A-num × S-num	1,55	2941	1.21	.28	1,47	1948	0.76	.39	1,93	0.46	.5
3-Way interaction	1,55	3871	1.67	.20	1,47	3319	1.21	.28	1,96	0.70	.4
<i>Region 6 (verb)</i>											
Grammaticality	1,55	942	0.3	.59	1,47	1831	0.72	.40	1,92	0.21	.65
Attractor number	1,55	1443	0.61	.44	1,47	261	<0.1	.80	1,57	<0.1	.81
Subject number	1,55	35,005	11.6	.001	1,47	31,055	11.4	.001	1,101	5.76	.02
Att-Num × gram.	1,55	540	0.22	.64	1,47	61	0.02	.88	1,56	<0.1	.89
Sub-Num × gram	1,55	717	0.25	.62	1,47	1477	0.45	.50	1,98	0.16	.69
A-num × S-num	1,55	1	<0.1	.99	1,47	12	<0.1	.96	1,64	<0.1	.99
3-Way interaction	1,55	7927	2.39	.13	1,47	6128	1.79	.19	1,7	1.02	.32
<i>Region 7 (verb + 1)</i>											
Grammaticality	1,55	363,776	28.6	<.001	1,47	251,224	42.1	<.001	1,101	17	<.001
Attractor number	1,55	11,147	1.81	.18	1,47	4380	1.12	.29	1,93	0.69	.41
Subject number	1,55	4289	0.45	.50	1,47	1817	0.45	.51	1,101	0.22	.64
Att-Num × gram.	1,55	19,253	3.48	.07	1,47	13675	1.89	.18	1,89	1.23	.27
Sub-Num × gram	1,55	2216	0.54	.47	1,47	141	<0.1	.86	1,52	<0.1	.86
A-num × S-num	1,55	130	<0.1	.89	1,47	1517	0.29	.59	1,62	<0.1	.89
3-Way interaction	1,55	1044	0.30	.58	1,47	5546	1.37	.25	1,78	0.25	.62
<i>Region 8 (verb + 2)</i>											
Grammaticality	1,55	5540	1.39	.24	1,47	1566	0.47	.50	1,77	0.35	.56
Attractor number	1,55	2723	0.92	.34	1,47	2785	1.04	.31	1,102	0.49	.49
Subject number	1,55	45	<0.1	.90	1,47	49	0.02	.90	1,102	<0.1	.9
Att-Num × gram.	1,55	7739	2.65	.11	1,47	9174	2.85	.10	1,102	1.37	.24
Sub-Num × gram	1,55	4338	1.30	.26	1,47	2174	0.90	.35	1,95	0.53	.47
A-num × S-num	1,55	1501	0.61	.44	1,47	545	0.25	.62	1,82	0.18	.67
3-Way interaction	1,55	27,327	6.03	.02	1,47	31,886	7.68	.01	1,102	3.38	.07

Inspection of the means suggested that the plural-attractor/plural-subject conditions were answered less accurately than the other conditions. A post-hoc comparison revealed a reliable effect of the presence of two plural nouns (plural attractor and subject), compared to one or none (mean of zero or one plurals = 94.5%; mean of two plurals = 91.2%; $p < .01$).

Self-paced reading

The results of Experiment 3 are plotted in Fig. 3 (singular-subject conditions) and Fig. 4 (plural-subject conditions). In Regions 2 and 3, the relative clause head and relative pronoun, the omnibus ANOVA showed a main ef-

fect of attractor number, as in Experiment 2, due to slower reading times for the plural head conditions (R2: plural mean = 353 ms, singular mean = 341 ms, 95% CI = 6.5 ms, $p < .01$; R3: plural mean = 339 ms, singular mean = 331 ms, 95% CI = 4.8 ms, $p < .05$). The 2×2 ANOVAs, split by subject number, revealed that singular-subject conditions show this effect more strongly in Region 2, and plural-subject conditions in Region 3; this variation in timing was presumably random, as subject number was not manipulated until later in the sentence. In the by-items analysis there was a significant effect of subject number at Region 4. Region 5, the relative clause subject region, showed both main effects of attractor number and subject number (RC

Table 6

Experiment 3: Repeated measures analysis of variance by RC subject number. First number is 2 × 2 for RC Subject = singular, second number is 2 × 2 for RC Subject = plural. ANOVA tests reliable at $\alpha = 0.05$ in bold.

	By participants				By items				MinF		
	df	MS _{effect}	F ₁	p	df	MS _{effect}	F ₂	p	df	minF	p
<i>Region 2 (RC head)</i>											
Grammaticality	1,55	1354 1	0.65 <0.1	.43 .98	1,47	2682 314	1.79 0.16	.19 .69	1,88 1,55	0.47 <0.1	.49 .98
Attractor numb.	1,55	28,383 1021	9.4 0.35	<.01 .56	1,47	19,721 755	7.39 0.31	.01 .58	1,98 1,100	4.14 0.17	.04 .68
Number × gram.	1,55	7950 1894	4.19 0.84	.05 .36	1,47	2974 781	0.95 0.31	.33 .58	1,68 1,79	0.78 0.23	.38 .63
<i>Region 3 ('who')</i>											
Grammaticality	1,55	451 15	0.35 <0.1	.56 .92	1,47	115 530	<0.1 0.34	.79 .56	1,66 1,56	<0.1 <0.1	.81 .92
Attractor number	1,55	1305 9480	0.54 9.1	.47 <.01	1,47	393 6514	0.29 6.35	.59 .02	1,89 1,96	0.19 3.74	.66 .06
Number × gram.	1,55	2319 2110	0.35 1.87	.56 .18	1,47	1478 1978	0.84 0.86	.36 .36	1,92 1,85	0.25 0.59	.62 .44
<i>Region 5 (RC subj.)</i>											
Grammaticality	1,55	155 2494	<0.1 0.78	.78 .38	1,47	2 5687	<0.1 2.2	.98 .14	1,48 1,85	<0.1 0.57	.98 .45
Attractor number	1,55	2581 16,255	0.98 7.85	.33 .01	1,47	1729 10,815	0.36 3.86	.36 .06	1,100 1,87	0.46 2.59	.5 .11
Number × gram.	1,55	559 4140	0.27 1.76	.61 .19	1,47	6 7036	<0.1 1.78	.96 .19	1,48 1,101	<0.1 0.88	.96 .35
<i>Region 6 (verb)</i>											
Grammaticality	1,55	8 1651	<0.1 0.42	.95 .52	1,47	10 3299	<0.1 1.1	.95 .3	1,101 1,87	<0.1 0.31	.97 .58
Attractor number	1,55	677 767	0.27 0.2	.6 .66	1,47	194 80	<0.1 <0.1	.84 .89	1,61 1,55	<0.1 <0.1	.84 .89
Number × gram.	1,55	6302 2165	2.14 0.74	.15 .39	1,47	3708 2482	1.13 0.82	.29 .37	1,89 1,102	0.74 0.39	.39 .53
<i>Region 7 (verb + 1)</i>											
Grammaticality	1,55	154,603 211,389	18.2 25.5	<.001 <.001	1,47	131,642 119,723	17.8 38.1	<.001 <.001	1,101 1,98	25.5 38.1	<.001 <.001
Attractor number	1,55	4436 6841	0.93 0.87	.34 .36	1,47	5527 371	1.11 <0.1	.3 .77	1,102 1,57	0.51 <0.1	.48 .36
Number × gram.	1,55	14,631 5666	3.40 1.22	.07 .27	1,47	18,319 902	3.84 0.14	.06 .71	1,102 1,58	1.8 0.12	.18 .73
<i>Region 8 (verb + 2)</i>											
Grammaticality	1,55	37 9841	<0.1 2.12	.91 .15	1,47	25 3715	<0.1 1.37	.78 .25	1,73 1,93	<0.1 0.83	.92 .36
Attractor number	1,55	4135 90	1.44 <0.1	.24 .85	1,47	2896 433	0.93 0.26	.34 .62	1,94 1,70	0.56 <0.1	.46 .86
Number × gram.	1,55	32,075 2991	8.52 0.81	<.01 .37	1,47	37,633 3427	8.63 1.14	.01 .29	1,101 1,101	4.29 0.47	.04 .49

subject number: plural mean = 337 ms, singular mean = 329 ms, 95% CI = 6.5 ms, $p < .05$; attractor number: plural mean = 339 ms, singular mean = 327 ms, 95% CI = 6.4 ms, $p < .05$). The effect of subject number in these regions appeared to be largely carried by an exceptional value for grammatical plural-attractor/plural-subject conditions, which may reflect an additional cost of having to keep track of two plural features. At the verb in Region 6 there was a clear effect of RC subject number (plural mean = 365 ms, singular mean = 348 ms, 95% CI = 7.5 ms, $p < .005$). Region 7, the region following the critical verb, showed a main effect of grammaticality (mean ungrammatical = 403 ms; mean grammatical = 355 ms; 95% CI = 13.1 ms, $p < .005$), and a marginal interaction of grammaticality and attractor number. In Region 8, the 3-way interaction of grammaticality, attractor number, and subject number was significant by participants and items.

However, splitting the design by relative clause subject number revealed a pattern of attraction similar to Experiment 2, but only for singular subjects. For singular subjects, the plural-attractor conditions showed a smaller grammaticality effect than the singular attractor conditions, which was marginally significant in Region 7 (Grammaticality:Ungram × RC Head:Pl $\Delta\mu = -33$ ms; 95% CI = 37 ms, $p < .10$) and was significant in Region 8 (Grammaticality:Ungram × RC Head:Pl $\Delta\mu = -50$ ms; 95% CI = 32 ms, $p < .01$). By comparison, attractor number had no impact upon the grammaticality effect for plural RC subjects in either post-verbal region (R7 Grammaticality:Ungram × RC Head:Pl $\Delta\mu = -16$ ms; 95% CI = 37 ms; R8 $\Delta\mu = 14$ ms; 95% CI = 29). Note that whereas in Experiment 2 the plural attractor completely eliminated the dis-

ruption due to subject–verb mismatch, in Experiment 3 the disruption was merely reduced; however, the reason for this variation in effect size is unclear, as both experiments contained the same items in these conditions.

As in Experiment 2, we further tested for the existence of attraction effects in the grammatical conditions by conducting pairwise comparisons between singular and plural-attractor conditions in grammatical sentences, for both singular and plural subject sets in the region following the critical verb (R7). We found no significant effects of attractor in either the grammatical singular-subject conditions (R7: plural mean = 356 ms, singular mean = 348 ms, 95% CI = 15.4 ms, $p > .1$; R8: plural mean = 361 ms, singular mean = 345 ms, 95% CI = 17.1 ms, $p > .1$) or the grammatical plural-subject conditions (R7: plural mean = 358 ms, singular mean = 355 ms, 95% CI = 14.6 ms, $p > .1$; R8: plural mean = 344 ms, singular mean = 353 ms, 95% CI = 15.2 ms, $p > .1$).

Discussion

As in Experiment 2 we found that the presence of a plural attractor in the RC-head position reduced the disruption due to ungrammatical subject–verb mismatch when the subject was singular. Furthermore, Experiment 3 showed that this attractor effect did not appear when the subject was plural; in this case, both ungrammatical conditions showed equal disruption relative to the grammatical baseline. This finding mirrors the same markedness pattern shown in previous literature on agreement attraction in production and comprehension of other constructions (Bock & Miller, 1991; Pearlmutter et al., 1999) and thus supports the idea that the attraction effect shown here

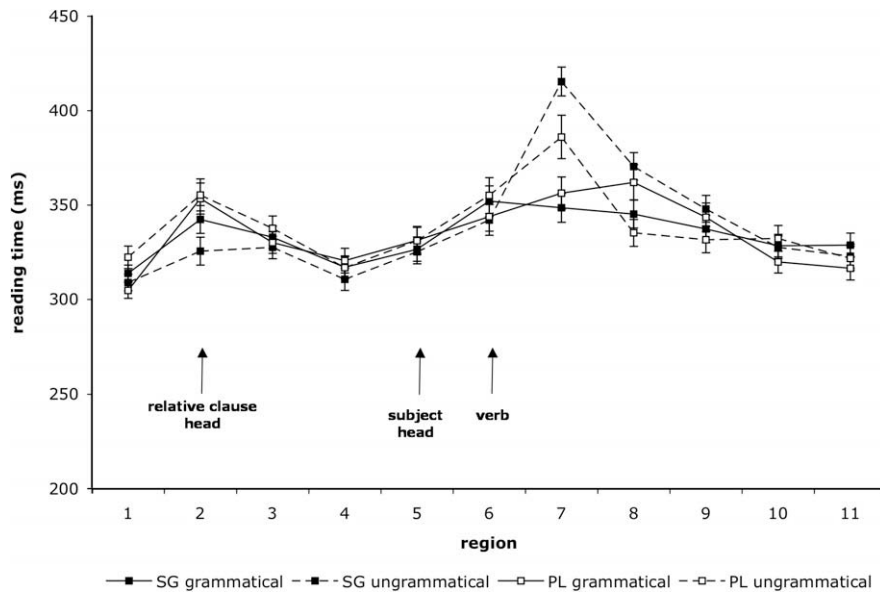


Fig. 3. Experiment 3: Self-paced reading results: singular relative clause subjects. Region by region means segregated by relative clause head number and grammaticality. Error bars indicate standard error of the mean. *Sample sentence:* The₁ musician(s)₂ who₃ the₄ reviewer₅ praise(s)₆ so₇ highly₈ will₉ probably₁₀ win(s)₁₁...

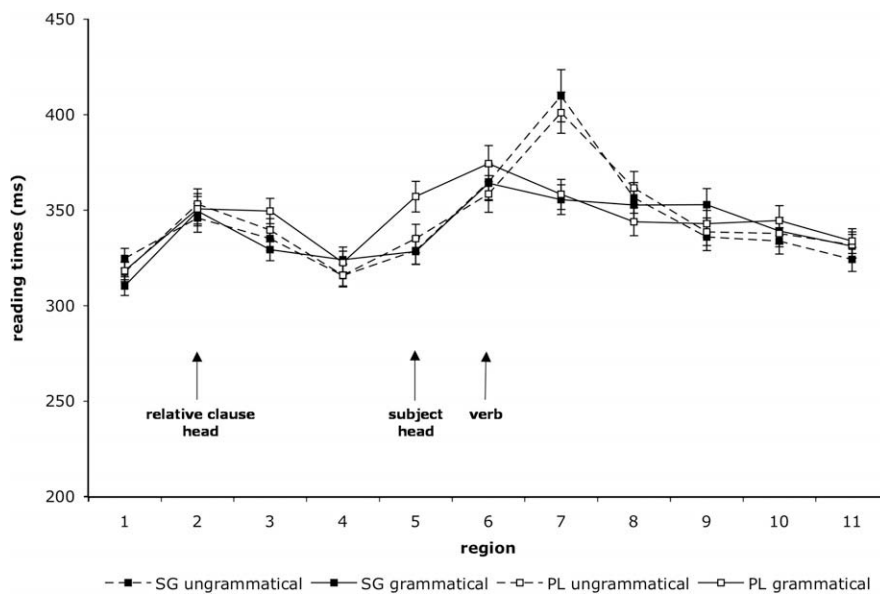


Fig. 4. Experiment 3: Self-paced reading results: plural relative clause subjects. Region by region means segregated by relative clause head number and grammaticality. Error bars indicate standard error of the mean. *Sample sentence:* The₁ musician(s)₂ who₃ the₄ reviewer₅ praise(s)₆ so₇ highly₈ will₉ probably₁₀ win(s)₁₁...

has a similar basis, despite the different ordering of attractor and subject. Taken together, the results of Experiments 2 and 3 argue against a percolation account of agreement attraction in comprehension. Such accounts predict that the RC head should act only as a weak attractor at best, because of its structural relationship with the RC subject. However, we found strong attractor effects for this configuration in the standard agreement attraction pattern:

attraction for singular-subject/plural-attractor conditions and not vice versa.

Although the finding of attraction in relative clause configurations argues against the classic percolation model, they do not argue conclusively against models that explain attraction through faulty representation of the subject. It might be possible to create a percolation model both in which percolation can occur downwards and in which

the weights are arranged such that the structural distance effects observed in production studies of attraction are still predicted, but that both relatively close and relatively distant attractors can exert strong effects in comprehension. Relatedly, the model of Eberhard and colleagues (2005) leaves open the possibility for features to spread more freely than in percolation models, such that there could be a combination of parameter settings which would predict strong attraction effects even for structurally distant attractors. Such a less-constrained model might also draw on the fact that the RC head must be reactivated at the verb for thematic reasons, and could posit that the attractor features are spread to the subject representation during this operation.

However the second major finding of Experiments 2 and 3 is much harder to explain for models that attribute attraction effects to internally inconsistent representations of the subject phrase. While in both Experiments 2 and 3 we found attractor effects in singular-subject conditions, we found no parallel 'reverse' attractor effect in grammatical conditions, for either singular- or plural-subject conditions. In other words, the presence of an attractor noun mismatching the verb in number had no effect on reading times as long as the subject and verb did match in number. However, models of attraction in which number features spread among the previously processed elements of a sentence predict that the presence of a mismatching attractor noun should often lead to the wrong number-marking on the subject, with the consequence that a grammatical sentence should appear to the parser to be ungrammatical when the verb is encountered. The size of this increase in disruption should mirror the size of the reduction in disruption for attraction in ungrammatical sentences, because it is the same phenomenon that is assumed to drive both—feature spreading among the elements prior to the verb.

A potential concern about this logic is that even if feature percolation leads to a symmetric distribution of attraction in grammatical and ungrammatical sentences, the effect of attraction on mean reading times might be asymmetric. However, if we think of the reading time distribution for attractor sentences as sampled from two underlying RT distributions, one corresponding to 'perceived grammatical' and the other 'perceived ungrammatical', in proportions determined by the attraction rate, then the effect on the means should be linear and is thus expected to be symmetric. Analytically, the expectation value of two independently sampled distributions is a linear combination of the expected values of the two distributions (Brunk, 1975). We have confirmed this to be true by simulation for the positively skewed ex-Gaussian distribution that describes reaction times (Luce, 1986; see *Supplementary Materials*).

Although our failure to find attraction effects in grammatical sentences presents a major challenge to theories which attribute attraction to faulty representation of subject number, some previous work has shown evidence for increased disruption in grammatical sentences with a mismatching attractor (Nicol et al., 1997; Pearlmutter et al., 1999; Häussler & Bader, 2009). These experiments differed from Experiments 2 and 3 in the configuration used, the local environment for the disruption, and in some cases, in

methodology. In Experiments 4–6, we attempt to resolve these conflicting results.

Experiment 4

Experiments 2 and 3 showed an attraction effect in ungrammatical singular-subject sentences, but not in grammatical sentences. In all conditions where the subject agreed with the verb, we found no cost associated with the presence of an attractor that mismatched the verb. Only in ungrammatical sentences where the subject was singular and mismatched in number with the plural verb did the number of the attractor have an effect on reading times. However, Pearlmutter and colleagues (1999) report effects of attractor number in grammatical sentences in self-paced reading for prepositional-modifier constructions.

One possible explanation for the divergence in results is that attraction effects in grammatical sentences depend for some reason on the subject-attractor-verb order of the PP-modifier construction. For example, percolation might be delayed in the relative clause constructions until the relative clause head is retrieved at the verb. If the additional assumption is made that the grammatical sentences are processed faster than the ungrammatical sentences, one could claim that percolation proceeds too slowly to affect the grammatical conditions but just fast enough to affect the ungrammatical conditions. In order to address this and related concerns, we used the prepositional-modifier construction in the remaining four experiments, in which we focus on the existence of attractor effects in grammatical sentences.

Another possible explanation for the different results is that the effect of attractor number observed by Pearlmutter et al. (1999) in the grammatical conditions may have been due to differences in the cost of processing the singular or plural attractor noun in the region prior to the verb. In Experiments 1–3 we saw significantly longer reading times associated with plural nouns, often in the region following the noun. As discussed in the Introduction, this confounding factor is a particular concern in the prepositional cases for the grammatical comparison, because the condition containing the potentially more complex plural is also the one that the percolation theory predicts to show an attraction-related slow-down, whereas in the ungrammatical conditions the predictions go in opposite directions (plural attractor reduces slow-down). The potential for confusion in interpreting these effects is exacerbated by the fact that in Experiments 2 and 3 both number and attraction effects tended to be found not on the noun or verb itself but on the subsequent word (this was also true for at least a subset of the attraction effects observed by Pearlmutter et al., 1999, in self-paced reading and eye tracking).

In Experiment 4 we examined prepositional-modifier constructions in self-paced reading, using materials similar to those tested by Pearlmutter et al., 1999. However, as in Experiment 1, an adverb was inserted between the attractor noun and the verb. Although effects of plural complexity may extend beyond the adverb, depending on their source, reading times on the adverb region provide an index of effects of noun number independent of the verb.

Participants

Participants were 46 native speakers of English from the University of Maryland community with no history of language disorders.

Materials

Experimental materials consisted of 24 sentence sets arranged in a 2×2 design with attractor number (singular/plural) and grammaticality (grammatical/ungrammatical) as factors. As in Experiment 1, 16 of the sentences were modified versions of materials used in Pearlmutter et al. (1999); an example set is presented in Table 7. The subject of the sentence was always singular, and grammaticality was manipulated by varying the number of the verb (singular = grammatical, plural = ungrammatical). The first seven words of each experimental item always followed the same sequence: *determiner-noun-preposition-determiner-noun-adverb-verb*. Since singular and plural attractors differ in both number of characters and morphological complexity, the adverb was included to provide an index of effects of noun number on setting before the critical verb region. In an effort to further minimize effects of noun number, the attractor nouns were chosen such that on average across items they occurred equally frequently in the singular or the plural according to the Cobuild Bank of English corpus. The word following the critical verb was either an adjective or a past participle and never carried agreement. The 24 sets of four conditions were distributed across four lists in a Latin Square design, and combined with 48 relative-clause agreement attraction sentences similar to those described in Experiments 2 and 3 (half ungrammatical) for a separate manipulation not discussed here, and 200 grammatical filler sentences of similar length. This resulted in 13% of the items being ungrammatical.

Procedure

The same self-paced reading procedure was used as in Experiment 1, and the analysis followed the same steps. Reading times that exceeded a threshold of 2.5 s.d. by region and condition were excluded. One participant showed a comprehension question accuracy rate of less than 80% across all items and was thus excluded from further analyses. Due to experimenter error, the distribution of participants across the four lists was unbalanced. In the analysis presented here, one further participant was excluded such that 44 participants were evenly balanced across the lists; however, the pattern of results did not differ from the analysis in which this participant was included.

Table 7

Sample set of experimental items for Experiments 4–6. Note that the adverb region was included in Experiments 4 and 6 only.

<i>Grammatical items (Experiments 4–6)</i>	
Singular attractor/grammatical	The key to the cell (unsurprisingly) was rusty from many years of disuse
Plural attractor/grammatical	The key to the cells (unsurprisingly) was rusty from many years of disuse
<i>Ungrammatical items (Experiments 4 and 5)</i>	
Singular attractor/ungrammatical	The key to the cell (unsurprisingly) were rusty from many years of disuse
Plural attractor/ungrammatical	The key to the cells (unsurprisingly) were rusty from many years of disuse

Data for each of the first 10 regions of the sentence were entered into a 2×2 repeated-measures ANOVA with attractor number and grammaticality as factors. Regions of interest were 5–10; the attractor noun appeared in Region 5, and the critical verb appeared in Region 7. Statistics for each of these six regions are presented in Table 8.

Results

Comprehension question accuracy

The mean comprehension question accuracy was 89.6%. For grammatical conditions, mean accuracy for the singular attractor condition was $94.3 \pm 1.5\%$ compared to $85.2 \pm 2.2\%$ in the plural-attractor condition; for ungrammatical conditions, mean accuracy for the singular attractor condition was $89.0 \pm 2.2\%$ compared to $89.8 \pm 2.2\%$ in the plural-attractor condition. There was a reliable effect of attractor number ($p < .001$), and a reliable interaction with grammaticality ($p < .01$).

Self-paced reading

The results of Experiment 4 are presented in Fig. 5 (Panel A). Regions 1–4 showed no significant effects. The attractor noun (R5) showed a main effect of number (singular mean = 284 ms; plural mean = 308 ms; 95% CI = 8.5 ms; $p < .001$). Since the effect preceded the critical verb, the difference likely reflects the additional complexity of reading plurals vs. singulars, as was observed in Experiments 1–3. The effect persisted in the adverb region (R6). At the critical verb (R7) there was an effect of grammaticality (grammatical mean = 332 ms; ungrammatical mean = 347 ms; 95% CI = 9.7; $p < .05$) and an interaction with attractor number. In the region following the verb (Region 8) there was a more pronounced main effect of grammaticality (ungrammatical mean = 349 ms; grammatical mean = 317 ms; 95% CI = 9.7 ms; $p < .001$), as well as again a significant grammaticality \times attractor number interaction. The subsequent region (Region 9) also showed the same pattern. Finally, a main effect of grammaticality was observed at Region 11.

In order to test whether these effects reflected attraction we conducted pairwise comparisons between singular and plural-attractor conditions at the verb (R7) and the region following the verb (R8) for grammatical and ungrammatical sentences separately. At the verb (R7), pairwise comparisons showed that there was no significant difference due to attractor number for the two ungrammatical conditions (singular mean = 351 ms; plural mean = 344 ms; 95% CI = 15.4; $p > .1$), but there was a difference for the two grammatical conditions (singular mean = 324 ms; plural mean = 341 ms; 95% CI = 14.5; $p < .005$). However, given that the region immediately prior to the

Table 8Experiment 4: Omnibus repeated measures analysis of variance. ANOVA tests reliable at $\alpha = 0.05$ highlighted in bold.

	By participants				By items				MinF		
	df	MS _{effect}	F ₁	p	df	MS _{effect}	F ₂	p	df	minF	p
<i>Region 5 (attractor)</i>											
Grammaticality	1,43	9	<0.1	.93	1,23	209	0.15	.70	1,47	<0.1	.92
Attractor number	1,43	17,073	10.9	<.01	1,23	14,163	12.8	<.01	1,63	5.88	.02
Number × gram.	1,43	5243	2.71	.11	1,23	766.8	0.62	.44	1,34	0.50	.48
<i>Region 6 (adverb)</i>											
Grammaticality	1,43	96	<0.1	.84	1,23	19	<0.1	.91	1,37	<0.1	.92
Attractor number	1,43	17,180	5.1	.03	1,23	10,507	5.76	.02	1,62	2.70	.11
Number × gram.	1,43	1070	0.58	.45	1,23	11	<0.1	.94	1,23	<0.1	.92
<i>Region 7 (verb)</i>											
Grammaticality	1,43	12,000	5.1	.03	1,23	6688	4.55	.04	1,58	2.41	.13
Attractor number	1,43	3	<0.1	.97	1,23	724	0.26	.62	1,43	<0.1	1
Number × gram.	1,43	16,963	7.77	.01	1,23	2540	1.5	.23	1,32	1.26	.27
<i>Region 8 (verb + 1)</i>											
Grammaticality	1,43	37,681	15.3	<.001	1,23	27,042	27.0	<.001	1,66	9.76	<.01
Attractor number	1,43	6074	2.09	.16	1,23	3662	2.32	.14	1,62	1.10	.3
Number × gram.	1,43	21,399	9.91	<.01	1,23	7962	3.31	.08	1,39	2.48	.12
<i>Region 9 (verb + 2)</i>											
Grammaticality	1,43	27,089	21.1	<.001	1,23	14,408	23.4	<.001	1,62	11.1	.001
Attractor number	1,43	4428	2.97	.09	1,23	1855	1.84	.19	1,50	1.14	.29
Number × gram.	1,43	10,368	10.3	<.01	1,23	4302	3.08	.09	1,37	2.37	.13
<i>Region 10 (verb + 3)</i>											
Grammaticality	1,43	2708	1.5	.23	1,23	2296	2.34	.14	1,66	0.91	.34
Attractor number	1,43	552	0.38	.54	1,23	104	<0.1	.78	1,33	<0.1	.79
Number × gram.	1,43	4634	4	.05	1,23	841	0.8	.38	1,32	0.66	.42
<i>Region 11 (verb + 4)</i>											
Grammaticality	1,43	18,134	17.5	<.001	1,23	12,543	10.5	<.01	1,49	6.55	.01
Attractor number	1,43	338	0.35	.56	1,23	532	0.61	.44	1,66	0.22	.64
Number × gram.	1,43	958	0.6	.44	1,23	6	<0.1	.94	1,23	<0.1	.92

verb also showed reading times for the plural attractor case to be significantly longer, it is difficult to unambiguously interpret this difference as an attraction effect. In contrast, in the region following the verb (R8), we found reading times in the plural attractor case to be significantly faster in the ungrammatical conditions (singular mean = 365 ms; plural mean = 333 ms; 95% CI = 15.8 ms; $p < .005$). There was no reliable difference in the grammatical conditions (singular mean = 313 ms; plural mean = 321 ms; 95% CI = 12.6 ms; $p > .1$).

Discussion

The results of Experiment 4 replicated previous demonstrations that agreement attraction from a prepositional modifier reduces the disruption caused by an ungrammatical subject–verb mismatch. However, in contrast to some previous reports, the regions showing the attraction effect (the regions immediately following the verb) did not show a corresponding effect in the grammatical conditions. We did, however, find a modest main effect of attractor number on the attractor noun itself, which continued through the subsequent adverb region, and continued to the verb in grammatical conditions. This effect is likely due to differences in processing cost for singular and plural nouns. The size of the number effect (noun region: 24 ms; adverb region: 17 ms) was smaller than that observed in Experiment 1, but was in line with the size of effects seen in other studies (~15 ms: Lau et al., 2007).

The lack of an attraction effect for grammatical sentences in the prepositional-modifier construction is consistent with Experiments 2 and 3, in which we also failed to find effects of attractor number for grammatical sentences. These findings conflict with the predictions of models discussed above in which feature-spreading causes attraction effects in creating an internally inconsistent representation of subject number. However, the findings of Experiment 4 must be considered cautiously given the previous results that did show attraction effects for grammatical sentences (Nicol et al., 1997; Pearlmutter et al., 1999). In Experiment 5, we replicate Experiment 4 using materials that are more similar to those used in previous studies.

Experiment 5

Experiment 4 showed that when an adverb intervened between the attractor and the verb in prepositional-modifier constructions, a clear attraction effect was seen only in ungrammatical sentences. We observed significant differences before the verb was ever encountered, which seemed to be due to increased processing requirements for plural nouns. These differences began at the noun and extended into the verb region. In contrast, the classic attraction effect for ungrammatical sentences did not become significant until the region following the verb, as in Experiments 2 and 3. We suggested that costs due to the

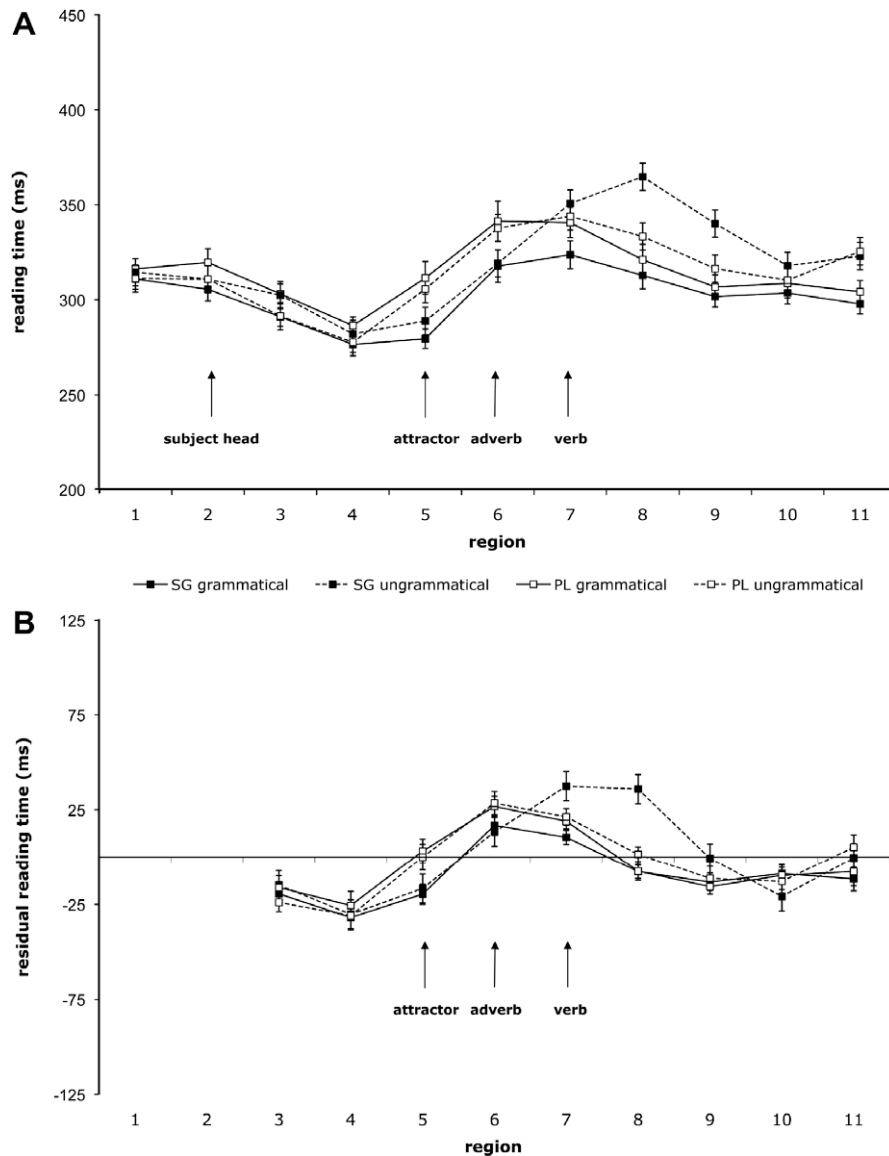


Fig. 5. Experiment 4: Self-paced reading results. *Panel A:* Region by region means segregated by attractor number and grammaticality. Error bars indicate standard error of the mean. *Panel B:* Region by region residual means based on a mixed-effects model that incorporated previous region reading times. *Sample sentence:* The₁ key₂ to the₃ cabinet(s)₄ unsurprisingly₅ was/were₇ rusty₈ from₉ many₁₀ years₁₁...

increased complexity of the plural may have resulted in an increase in reading time for plurals over singulars in self-paced reading. This may sometimes create the illusion of an early-onset attraction effect for grammatical sentences, particularly when an adverb is not included. In Experiment 5, we performed a more direct replication of previous studies by examining the attractor effect in the absence of the adverb.

Participants

Participants were 60 native speakers of English from the University of Maryland community with no history of language disorders.

Materials

The experimental materials consisted of 24 sentence sets arranged in a 2×2 design with attractor number (singular/plural) and grammaticality (grammatical/ungrammatical) as factors. Sentences were the same as those described in Experiment 4 but without the adverb between the attractor NP and the verb. Thus, the subject of the sentence was always singular, and grammaticality was manipulated by varying the number of the verb. The first six words of each experimental item always followed the same sequence: *determiner-noun-preposition-determiner-noun-verb*. The 24 sets of four conditions were distributed across 4 lists in a Latin Square design, and combined with

48 relative-clause agreement attraction sentences (half ungrammatical; described separately as Experiment 3), and 216 grammatical filler sentences of similar length. This resulted in 13% of the items being ungrammatical.

Procedure

The same self-paced reading procedure was used as in Experiment 1, and the analysis followed the same steps. Reading times that exceeded a threshold of 2.5 s.d. by region and condition were excluded. Due to experimenter error, the distribution of participants across the 8 lists was unbalanced. In the analysis presented here a subset of 56 participants were analyzed such that participants were evenly balanced across the lists; however, the pattern of results did not differ from the analysis in which all 60 participants were included.

Data for each of the first nine regions of the sentence were entered into a 2×2 repeated-measures ANOVA with attractor number and grammaticality as factors. Regions of interest were 5–9; the attractor noun appeared in Region 5, and the critical verb appeared in Region 6. Statistics for each of these five regions are presented in Table 9.

Results

Comprehension question accuracy

Mean comprehension question accuracy was 91.8%. For grammatical conditions, the singular mean was $93.3 \pm 1.3\%$ compared to the plural mean of $89.7 \pm 1.4\%$; for ungrammatical conditions, the singular mean was $89.7 \pm 1.7\%$ compared to the plural mean of $94.4 \pm 1.2\%$. Neither main

effect was reliable in a logistic mixed-effects model, but the interaction was reliable ($p < .05$).

Self-paced reading

As shown in Fig. 6 (Panel A), Regions 1–4 showed no significant effects. Region 5, the attractor region, showed a significant effect of number, but also a significant number \times grammaticality interaction. Post-hoc comparisons revealed that only the grammatical conditions showed a reliable number effect (singular mean = 303 ms; plural mean = 335 ms; 95% CI = 12.8 ms; $p < .005$), but not the ungrammatical conditions (singular mean = 317 ms; plural mean = 320 ms; 95% CI = 11.2; $p > .1$). Because the attractor precedes the critical verb, either the presence of a number effect in one comparison or its absence in the other must be spurious. Experiments 1, 2, and 4 all showed a main effect of number on the noun itself.

In the critical verb region (R6) there was also a main effect of number, such that conditions containing a plural attractor were read more slowly. There was no reliable interaction of number and grammaticality. In the region following the verb (R7) there was a main effect of grammaticality (ungrammatical mean = 386 ms; grammatical mean = 317 ms; 95% CI = 11.4 ms; $p < .005$), as well as a significant grammaticality \times attractor number interaction. The two subsequent regions (R8–9) showed the same pattern. The interaction was driven by a classic attraction pattern, specifically a smaller difference between the grammatical and ungrammatical conditions in the plural-attractor conditions than in the singular attractor conditions. Pairwise comparisons at the region following the verb (R7) for the grammatical and ungrammatical condi-

Table 9

Experiment 5: Omnibus repeated measures analysis of variance. ANOVA tests reliable at $\alpha = 0.05$ highlighted in bold.

	By participants				By items				MinP		
	df	MS _{effect}	F ₁	p	df	MS _{effect}	F ₂	p	df	minF'	p
<i>Region 5 (attractor)</i>											
Grammaticality	1,55	92	<0.1	.80	1,23	44.7	<0.1	.81	62	<0.1	.86
Attractor number	1,55	27,160	12.7	<.01	1,23	9050	5.85	.02	45	4.01	.05
Number \times gram.	1,55	10,609	5.65	.02	1,23	5475.4	8.56	<.01	74	3.40	.07
<i>Region 6 (verb)</i>											
Grammaticality	1,55	780	0.41	.52	1,23	614.5	0.72	.40	76	0.26	.61
Attractor number	1,55	11,293	5.25	.03	1,23	4188.2	4.24	.05	59	2.34	.13
Number \times gram.	1,55	2643	1.25	.27	1,23	2323.6	3.28	.08	78	0.91	.34
<i>Region 7 (verb + 1)</i>											
Grammaticality	1,55	275,561	59.3	<.001	1,23	114,352	56.5	<.001	64	28.9	<.001
Attractor number	1,55	35,484	9.24	<.01	1,23	14,903	7.33	<.01	59	4.09	.05
Number \times gram.	1,55	60,373	13.5	<.001	1,23	23,232	10.8	<.01	59	6.02	.02
<i>Region 8 (verb + 2)</i>											
Grammaticality	1,55	57,641	21.8	.001	1,23	24,761	21.2	<.001	64	10.8	<.01
Attractor number	1,55	302	<0.1	.76	1,23	814.9	0.82	.38	67	<0.1	.77
Number \times gram.	1,55	9226	3.9	.05	1,23	2623	2.67	.12	55	1.58	.21
<i>Region 9 (verb + 3)</i>											
Grammaticality	1,55	14,617	8.12	.01	1,23	5837	2.81	.11	40	2.09	.16
Attractor number	1,55	<1	<0.1	.99	1,23	11.4	<0.1	.89	55	<0.1	1
Number \times gram.	1,55	10,311	6.16	.02	1,23	3999	7.27	.01	69	3.33	.07
<i>Region 10 (verb + 4)</i>											
Grammaticality	1,55	1104	0.79	.38	1,23	346.1	0.49	.49	52	0.30	.59
Attractor number	1,55	127	<0.1	.76	1,23	9.9	<0.1	.91	29	<0.1	.92
Number \times gram.	1,55	5556	3.2	.08	1,23	1477.7	1.73	.20	49	1.12	.3

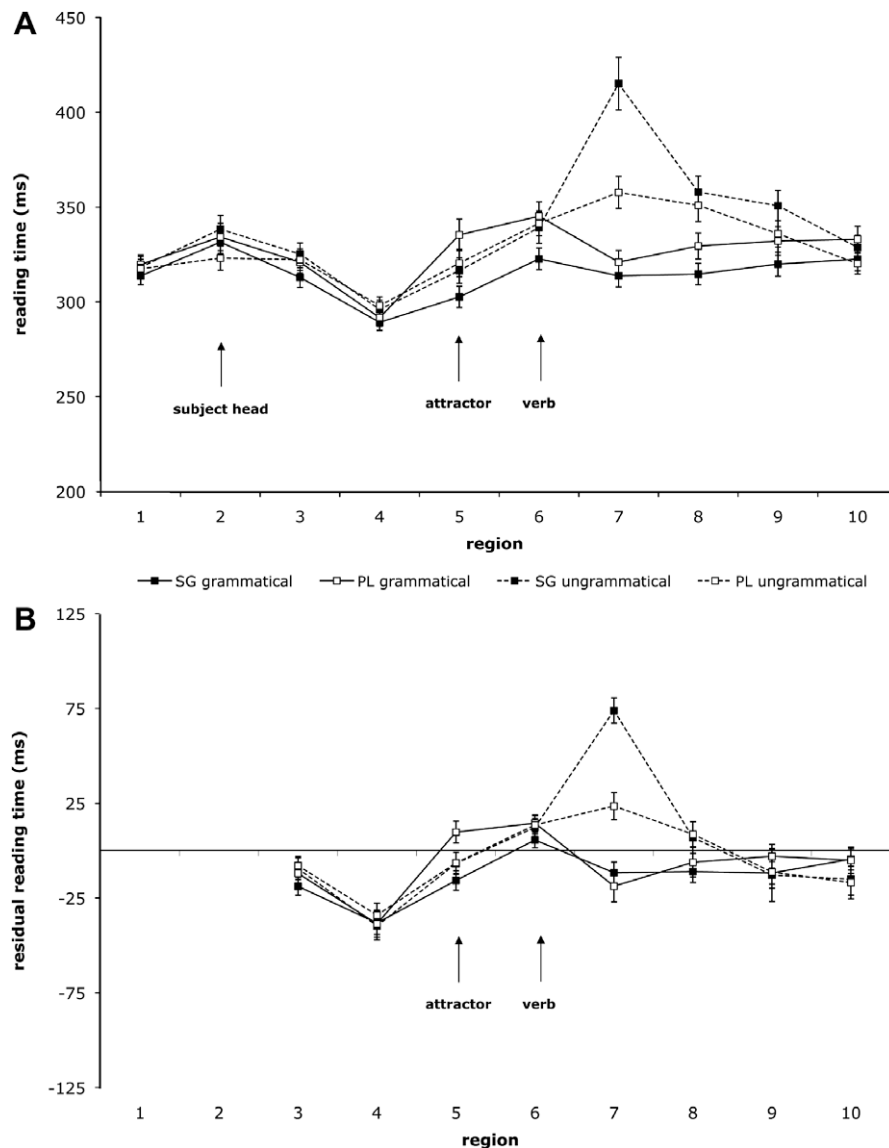


Fig. 6. Experiment 5: Self-paced reading results. *Panel A:* Region by region means segregated by attractor number and grammaticality. Error bars indicate standard error of the mean. *Panel B:* Region by region residual means based on a mixed-effects model that incorporated previous region reading times. *Sample sentence:* The₁ key₂ to₃ the₄ cabinet₅(s)₅ was/were₇ rusty₈ from₉ many₁₀ year₁₁...

tions separately showed significant differences due to attractor number for the two ungrammatical conditions (singular mean = 416 ms; plural mean = 358 ms; 95% CI = 24.5; $p < .005$), but not for the two grammatical conditions (singular mean = 314 ms; plural mean = 321 ms; 95% CI = 10.1 ms; $p > .1$). In Regions 8 and 9, the effect of attractor number in the two grammatical conditions was somewhat larger and marginally significant (R8: singular mean = 315 ms; plural mean = 329 ms; 95% CI = 11.4 ms; $p = .10$; R9: singular mean = 320 ms; plural mean = 332 ms; 95% CI = 10.9 ms; $p = .10$). In the ungrammatical conditions, however, there were no effects of attractor number in these regions (R8: singular mean = 357 ms; plural mean = 351 ms; 95% CI = 14.5 ms; $p > .1$; R9: singular

mean = 351 ms; plural mean = 336 ms; 95% CI = 12.4 ms; $p > .1$).

Discussion

The results of Experiment 5 were largely similar to those of Experiment 4. Main effects of number appeared in the attractor noun region and the subsequent verb region. In other words, although the grammatical conditions showed a significant effect of attractor on the critical verb, this effect was already present in the preceding region. Once again, effects of grammaticality and an interaction between grammaticality and attractor number appeared in the region following the verb, and paired comparisons showed a significant effect of attractor number for

ungrammatical conditions only. This pattern is consistent with previous results that suggest that attractor effects are largely delayed until the region following the verb, and that effects on the verb region itself likely reflect differences due to the increased complexity of plural nouns.

In contrast to Experiment 4, a small but significant effect of attractor number was seen for the grammatical pair in later regions of the sentence (Regions 8 and 9). Although this effect was not significant in Experiment 4, there was a numerical trend in the same direction. Combined, these data raise the possibility that grammatical sentences may indeed exhibit a real attraction effect, but that this effect is much smaller than the attractor effect for ungrammatical sentences and has a delayed time course. The small but significant effect of attraction and grammaticality on comprehension question accuracy is also consistent with the idea that an attraction effect for grammatical sentences may come online later in the sentence. At the same time, because the difference between the two grammatical conditions begins before the verb is encountered and remains at about the same size throughout the sentence, even the effects seen in the later regions may be due to baseline differences, if the plural cost observed stems from longer-lasting semantic/conceptual processes.

Previous region mixed-effect models analysis of Experiments 4 and 5

Experiments 4 and 5 showed that there was a large facilitation in reading times for ungrammatical sentences in the post-verbal regions when the sentence contained a plural attractor. In the same post-verbal regions there was no corresponding slow-down for grammatical sentences, counter to the predictions of a feature percolation account. However a slow-down was observed at the verb

for these sentences. We argued however that this slow-down reflected increased difficulty associated with reading a plural that was sustained in subsequent regions. In the following analyses, we test this claim by estimating region-by-region mixed-effects models that incorporate the previous region reading times as factors. It is therefore possible to effectively remove the RT dependency between adjacent regions and thus estimate the RT effects independently introduced by the critical verbal region (Vasishth, 2006).

Procedure

Raw reading times, trimmed according to the criteria reported above, were entered into linear mixed-effects models. Separate models were estimated for each experiment and each region beginning with R3. In addition to the experimental factors (grammaticality, attractor number, and their interaction), the reading times at the two previous regions, RT_{n-1} and RT_{n-2} , were treated as fixed effects. Participants and items were treated as random effects. Previous region reading times were also nested under participants, which provided a better fitting model. By means of likelihood ratio tests (Baayen et al., 2008), we found that nesting the other experimental factors under either participants or items did not improve the fit of the model in the regions of interest.

Trials were removed if either RT_n , RT_{n-1} or RT_{n-2} were outside the 2.5 s.d. region-by-condition exclusion criterion. Consequently slightly more data were removed from this analysis. On average by region, 97% of the trials analyzed in Experiment 4 were entered into this analysis; and 96% of the trials analyzed in Experiment 5 were analyzed here. Excluding these additional trials was not found to alter the pattern of results or reliability reported in Experiments 4

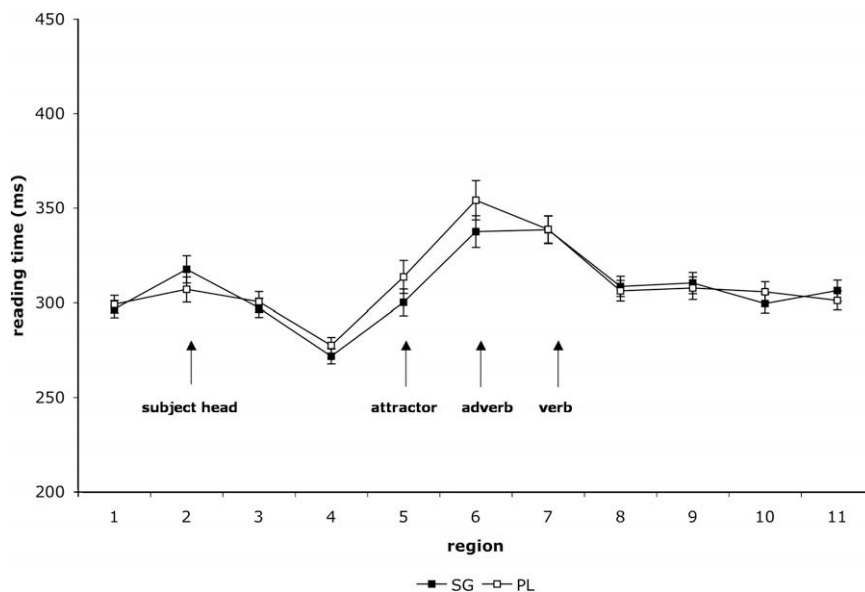


Fig. 7. Experiment 6: Self-paced reading results. Region by region means segregated by attractor number. Error bars indicate standard error of the mean. Sample sentence: The₁ key₂ to₃ the₄ cabinet(s)₅ unsurprisingly₆ was₇ rusty₈ from₉ many₁₀ years₁₁...

and 5 for raw reading times (that is, prior to considering previous region RT).

Results

Results are reported in two ways. Firstly, the specific treatment contrasts below come from linear mixed-effect models incorporating the two experimental factors and previous region RTs. Secondly, the B Panels in Figs. 5 and 6 provide a way of visualizing the specific impact of the previous region RT regression by plotting mean residual reading times of just a previous-regions RT model (that is, residualized without experimental factors). All RT_{n-1} and RT_{n-2} effects were significant, across regions and experiments. This is unsurprising since RTs within a sentence are expected to be correlated. RT_{n-1} and RT_{n-2} coefficients ranged from 0.17 to 0.77 (mean: 0.33; s.d.: 0.14).

In the Experiment 4 previous-regions RT analysis, a reliable slow-down for ungrammatical sentences occurred at the verb (R7; 13 ms; 95% CI = 10 ms, $p < .05$) and in the subsequent region (Region 8). This effect was largest in R8 (27 ms; 95% CI = 10 ms, $p < .001$). In the same region there was a reliable contrast between ungrammatical singular-attractor sentences and ungrammatical plural-attractor sentences, the latter being read significantly faster (31 ms; 95% CI = 18 ms, $p < .05$). There was a trend in the same direction already at the verb (Region 7), though it was not significant in the full model of the data. In a pairwise comparison restricted to just the ungrammatical conditions, the effect is significant (22 ms; 95% CI = 16 ms, $p < .05$). Crucially, neither in the verb region (R7) nor in any post-verbal region was there a reliable effect of the

attractor for grammatical sentences (R7: 3 ms; 95% CI = 12 ms, n.s.; R8: -2 ms; 95% CI = 11 ms, n.s.). In the attractor region (R5) a reliable effect of number was detected, such that plural-attractor sentences were read more slowly than singular-attractor sentences (17 ms; 95% CI = 9 ms, $p < .05$). This effect was confined to R5 and was not observed on the adverb region (R6).

In the Experiment 5 analysis a reliable slow-down for ungrammatical sentences occurred in the immediate post-verbal region (R7; 63 ms; 95% CI = 10 ms, $p < .001$) and in the subsequent region (R8; 19 ms; 95% CI = 8 ms; $p < .005$). In R7, where the largest grammaticality effect occurred, there was a reliable contrast between ungrammatical singular-attractor sentences and ungrammatical plural-attractor sentences, the latter being read much faster (33 ms; 95% CI = 21 ms; $p < .05$). Once again there were no significant effects of a plural attractor in grammatical sentences in any verbal or post-verbal region. There was a marginal effect of the plural attractor in R7, such that plural-attractor grammatical sentences were read faster than singular-attractor grammatical sentences (-18 ms; 95% CI = 15 ms; $p < .10$). In the attractor region (R5), a reliable effect of number was observed (12 ms; 95% CI = 7 ms; $p < .05$), but as in the raw reading time analysis this effect was confined to the comparison between grammatical sentences (28 ms; 95% CI = 9 ms; $p < .005$).

Discussion

The previous region RT analysis preserved some patterns observed in the raw RT analysis. Specifically, in the verbal and post-verbal regions there was a robust slow-

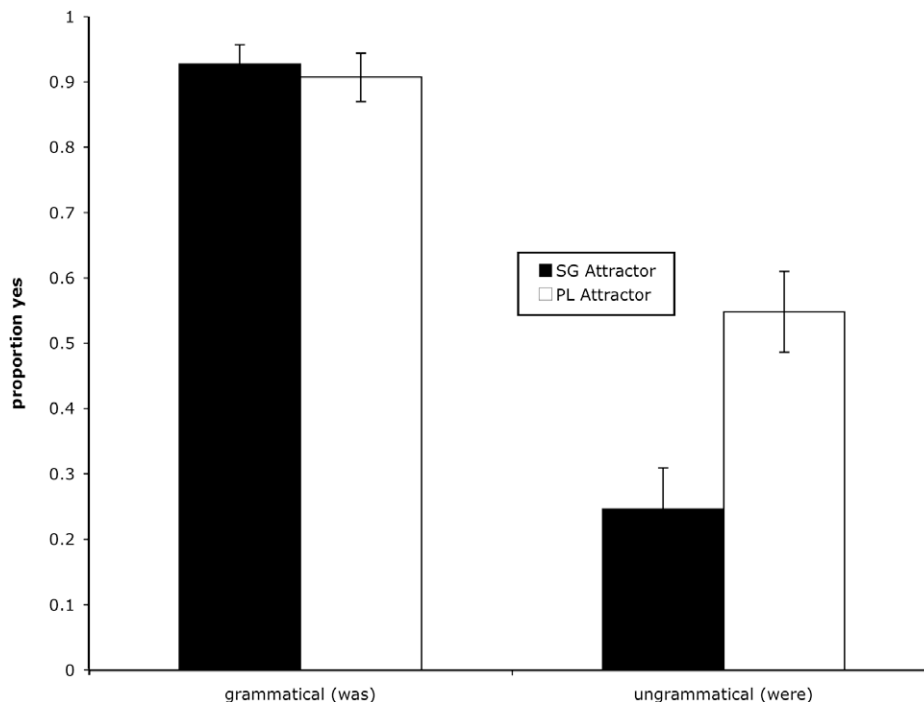


Fig. 8. Experiment 7: Speeded acceptability judgment results. Mean proportion 'acceptable' responses by grammaticality and attractor number. Error bars indicate standard error of the mean. *Sample sentence:* The key to the cabinets(s) was rusty from many years of disuse.

down for ungrammatical sentences and an attenuation of this slow-down in ungrammatical sentences containing a plural attractor; in the attractor region there was a slow-down for plural attractors (in 3 of 4 pairwise comparisons). However, notably absent from this analysis was any indication in the verbal or post-verbal regions that grammatical sentences were read more slowly when they contained a plural attractor. The comparison between Figs. 5 and 7 is helpful in determining the impact of incorporating previous region RTs in a model of region-by-region reading times. Both figures show that the slow-down first observed in the attractor region (R5) was present in both raw and residual datasets. In the raw reading times, this slow-down persisted to the adverb region (R6). However, once the correlations with previous region RTs were removed, no slow-down was evidenced in that region. Similarly no slow-down was present two regions from the attractor in grammatical conditions. Comparing Figs. 6 and 8 shows the same pattern. There was no difference between grammatical conditions beyond the attractor region.

We conclude that reading the verb does not introduce any independent difficulty for grammatical sentences when there is also a plural attractor in the sentence. This conclusion runs counter to the symmetry prediction of accounts that attribute attraction to misvaluing of the subject number, like feature percolation.

Experiment 6

Since the presence or absence of agreement attraction in grammatical sentences has significant consequences for theories of how agreement is computed in comprehension, in Experiment 6 we conducted a further test for a grammatical attraction effect in self-paced reading for the prepositional-modifier construction. In Experiment 6 we repeated the attraction manipulation of Experiment 4 (prepositional-modifier constructions with the 'buffer' adverb) but in this study we tested only the grammatical conditions and correspondingly doubled the number of items in each condition, reducing the within-subject variability.

If agreement attraction can occur in grammatical sentences, then we expect to see a reading time slow-down in the plural-attractor condition relative to the singular attractor condition.

Participants

Participants were 30 native speakers of English from the University of Maryland community with no history of language disorders.

Materials

Experimental materials consisted of 24 grammatical sentence pairs with singular subjects that varied in whether the attractor number matched or mismatched the number of the singular verb. Sentences were the same as those used in Experiment 4. The first seven words of each experimental item always followed the same sequence: *determiner-noun-preposition-determiner-noun-adverb-verb*. The 24 sets of two conditions were distributed across two lists in a Latin Square design, and were combined with 48 relative-clause agreement attraction sentences (half ungrammatical; described separately as Experiment 2), and 144 grammatical filler sentences of similar length. This resulted in 17% of the items being ungrammatical.

Procedure

The same self-paced reading procedure was used as in Experiment 1, and the analysis followed the same steps. Reading times that exceeded a threshold of 2.5 s.d. by region and condition were excluded. Two participants showed a comprehension question accuracy rate of less than 80% across all items and were thus excluded from further analysis.

Data for each of the first 10 regions of the sentence were entered into a repeated-measures ANOVA with attractor number as the factor of interest. Regions of interest were

Table 10
Experiment 6: Omnibus repeated measures analysis of variance.

	By participants				By items				MinF'			
	df	MS _{effect}	F ₁	p	df	MS _{effect}	F ₂	p	df	minF'	p	
<i>Region 5 (attractor)</i>												
Attractor number	1,27	2624	1.89	.18	1,23	5281	3.12	.09	1,49	1.18	.28	
<i>Region 6 (adverb)</i>												
Attractor number	1,27	7775	1.69	.21	1,23	5804	1.39	.25	1,48	0.76	.39	
<i>Region 7 (verb)</i>												
Attractor number	1,27	16	<0.1	.92	1,23	43	<0.1	.86	1,43	<0.1	.92	
<i>Region 8 (verb + 1)</i>												
Attractor number	1,27	209.5	0.19	.67	1,23	126	<0.1	.77	1,42	<0.1	.81	
<i>Region 9 (verb + 2)</i>												
Attractor number	1,27	403	0.31	.58	1,23	131	<0.1	.77	1,35	<0.1	.79	
<i>Region 10 (verb + 3)</i>												
Attractor number	1,27	831	0.71	.41	1,23	880	0.7	.41	1,50	0.35	.56	
<i>Region 11 (verb + 4)</i>												
Attractor number	1,27	1058	1.18	.29	1,23	702.8	0.74	.40	1,45	0.45	.51	

5–10; the attractor noun appeared in Region 5, and the critical verb appeared in Region 7. Statistics for each of these six regions are presented in Table 10.

Results

Comprehension question accuracy

Mean comprehension question accuracy was 92.0%. There was a main effect of attractor number (singular mean = 94.3 ± 1.2%; plural mean = 89.6 ± 2.0%; $p < .05$).

Self-paced reading

The results of Experiment 6 are presented in Fig. 7. Regions 1–4 showed no significant differences ($F_s < 1.7$), although there was a marginal effect in Region 2 in the participants analysis ($F_1(1, 27) = 3.2$; $p < .10$). This effect must be spurious, since the materials were identical at this and preceding regions. Neither the attractor noun region (R5) nor the adverb region (R6) showed a main effect of number. However, a pooled analysis of Regions 5 and 6 showed a reliable effect of attractor number (plural mean = 334 ms; singular mean = 319 ms; 95% CI: 9.0 ms, $p < .05$). Crucially, neither the critical verb region (R7) nor any of the regions following the verb (R8–10) showed a significant difference between the singular and plural-attractor conditions (R7 plural mean = 339 ms, singular mean = 338 ms, 95% CI = 12.0 ms; $p > .1$; maximal difference: R10 plural mean = 306 ms, singular mean = 300 ms, 95% CI = 8.1 ms; $p > .1$).

In order to increase the number of items per condition we did not test the corresponding ungrammatical sentences in Experiment 6, and thus there might be a concern that this particular group of participants happened not to be sensitive to attraction at all. However, this concern is mitigated by the fact that the relative-clause manipulation described in Experiment 2 was tested concurrently with the same participants in the same session, and these participants did show attraction effects in the ungrammatical relative-clause sentences.

Discussion

In Experiment 6 we tested attraction in grammatical prepositional-modifier constructions only and found no effects of attractor number on reading times at or after the critical verb. By itself, of course, this experiment is not sufficient to make a strong case against grammatical attraction, as it did not include the two ungrammatical attractor conditions to contrast with the null effect found in the grammatical conditions. However, when taken together with the previous four experiments these data provide strong evidence that grammatical sentences are not subject to attractor effects. The data from Experiment 6 replicate the results of Experiments 4 and 5 in which we also failed to find an effect of attractor number on reading times in the verb + 1 region for grammatical attraction constructions of the same type, as well as the results of Experiments 2 and 3 in which we failed to find an effect of attractor number on reading times following the verb in grammatical relative-clause attraction constructions. The only evidence in favor of an online attraction effect in grammatical sentences was the significant effect seen in later regions

(verb + 2 and verb + 3) in Experiment 4; however, this effect was later and much smaller than the attraction effect for ungrammatical sentences. Moreover the previous region RT analysis apportioned this effect to baseline differences in previous regions. The results of these five experiments thus converge to support the claim that agreement attraction either does not occur in the comprehension of grammatical sentences, or has a much different time course than attraction in ungrammatical sentences.

Although the effect of number at the attractor noun and the regions following the noun in Experiment 6 seemed to be weaker than in previous experiments, the plural conditions still showed a tendency for longer reading times in these regions, and the effect of number was significant when Regions 5 and 6 were combined. Thus, like the previous five experiments presented, this experiment provides evidence that noun number can exert small but reliable effects on reading times both on the noun itself and on the subsequent word, although the mechanisms underlying these effects are currently unclear.

Experiment 7

In Experiments 4 and 5 the additional processing complexity due to the plural attractor itself made it more difficult to determine whether slow-downs in the grammatical condition were due to a number effect or an attraction effect. Even when an adverb was inserted between the attractor and the verb, a main effect of noun number still extended as far as the verb region. In contrast to the RC experiments, in which the plural attractor was far from the verb and we were able to clearly show the absence of a grammatical attraction effect, it was more difficult in the PP-modifier experiments to unequivocally conclude from the reading time data that there was no grammatical attraction effect. In Experiment 7 we used an end-of-sentence judgment task to try to reduce the impact of number complexity on our measure. Agreement attraction should have the effect of increasing or decreasing sentence acceptability, but the processing complexity associated with plural nouns should have very little effect on acceptability. Furthermore, several previous studies have reported grammatical attraction effects in offline measures (Nicol et al., 1997; Häussler & Bader, 2009), which raises the possibility that agreement attraction does occur in grammatical sentences, but that its effects are for some reason delayed relative to ungrammatical sentences, and thus might be better captured with offline measures. Experiment 7 allowed us to examine this alternative possibility.

Participants

Participants were 16 native speakers of English from the University of Maryland community with no history of language disorders.

Materials

Experimental materials consisted of 24 grammatical sentence quadruplets using the prepositional-modifier

construction with singular subjects that varied in whether the attractor number matched or mismatched the number of the singular verb. Sentences were the same as those used in Experiment 5 (i.e., with no adverb between the attractor and the verb). The 24 sets of four conditions were distributed across four lists in a Latin Square design and were combined with 48 relative-clause agreement attraction sentences from a different experiment not reported here (half ungrammatical), 24 wh-dependency sentences from a different experiment (half ungrammatical) and 32 filler sentences of other types (half ungrammatical), for a total of 128 items.

Procedure

Sentences were presented one word at a time in the center of the screen with rapid serial visual presentation reading (RSVP; Potter, 1988) at a rate of 300 ms per word. At the end of each sentence, a response screen appeared for 2 s in which participants made a yes/no response by button press. Participants were instructed to read the sentences carefully and to judge whether they sounded like an acceptable sentence that a speaker of English might say. Participants were instructed to make their response as quickly as possible following the end of the sentence; if they waited longer than 2 s to respond, they were given feedback that their response was too slow.

Results

Fig. 8 shows the proportion of 'yes' judgments for the four experimental conditions in Experiment 7. The results of a 2×2 logistic mixed-effects model confirm what the figure suggests: there was a main effect of grammaticality (model coefficient, in logits, β : -4.0 ± 1.0 , $p < .001$) and an interaction of grammaticality with attractor number (β : 1.7 ± 1.3 , $p < .01$). Participants were more likely to accept ungrammatical sentences when an attractor was present: acceptance rates more than doubled ($N_{SG-N_{SG}}$ ungrammatical: $25 \pm 7\%$; $N_{SG-N_{PL}}$ ungrammatical: $55 \pm 6\%$). However, participants were not more likely to reject grammatical sentences, when there was an attractor ($N_{SG-N_{SG}}$ grammatical: $93 \pm 3.0\%$; $N_{SG-N_{PL}}$ grammatical: $91 \pm 3.7\%$; β : -0.26 ± 1.1 , n.s.).

Discussion

The results of Experiment 7 corroborate the results of Experiments 4–6. Consistent with the self-paced reading results, ungrammatical sentences containing a mismatch between a singular subject and a plural verb were more likely to be accepted in the presence of a plural attractor, and were judged acceptable 55% of the time, compared to 25% when a singular attractor was present. If attraction reflected errors in the encoding of subject number, then in grammatical sentences with plural attractors the singular verb would sometimes be perceived as mismatching the plural subject, and overall acceptability ratings would fall. However, no attractor effect was observed in acceptability judgments to the grammatical conditions. These data support our argument that the slow-downs observed immedi-

ately following the plural attractor in the self-paced reading experiments were due to increased processing cost of the plural and not to perceived subject–verb mismatch.

One possible alternative account of the self-paced reading experiments on the prepositional-modifier construction presented above would be that attraction effects appear earlier in grammatical sentences than in ungrammatical sentences. This would explain why only grammatical sentences showed an effect of attractor number at the critical verb region. However, although the time course of attraction is different for grammatical and ungrammatical sentences under this account, attraction should nevertheless be evident to the same extent for both in offline measures. Thus, the results of Experiment 7 provide evidence against this alternative.

General discussion

The results from the six subject–verb agreement attraction experiments presented here provide two types of evidence against accounts of agreement attraction in comprehension that rely on percolation, in particular, and on faulty representations of the subject, in general. In the two relative-clause experiments (Experiments 2 and 3), we found that even when a noun does not intervene between the subject and the verb and is in fact hierarchically superior to the subject noun, it can still exert a strong attraction effect, reducing or even eliminating reading time disruption due to an ungrammatical subject–verb mismatch. Furthermore, across all five self-paced reading attraction experiments we found no evidence for a corresponding attraction effect in grammatical sentences in the same time window. Although the interpretation of reading times is complicated in the prepositional-modifier construction by simple effects of noun number, we found that the effects observed on the verb could be completely explained by reading times on the previous regions. We found the same grammatical–ungrammatical attraction asymmetry in an RSVP acceptability judgment task, and we find no trace of an attraction effect on reading times in the grammatical relative clause cases, which do not suffer from the same confound. In the following we first review the implications for previous accounts of each type of evidence and then we discuss alternative accounts that could better capture the pattern of data we observe.

Attraction in a non-intervening configuration

Our results demonstrate that a seeming quirk of agreement, first pointed out by (Kimball & Aissen, 1971; e.g., "The people who Clark think are in the garden..."), is reflected in moment-to-moment processing. Kimball and Aissen speculated that the ability of a plural relative clause head to agree with the verb embedded within the relative clause was a matter of dialect, and, specifically, a dialect localized to the Northeastern US or Boston area. The one subsequent study to examine acceptability ratings for the Kimball and Aissen paradigm also likely drew largely on participants from this region (Clifton et al., 1999). However, in our study, participants largely came from

the Chesapeake Bay region and surrounding Mid-Atlantic states. It therefore seems less likely that agreement with the head of a relative clause is a fact about a regional dialect. Given how closely its processing profile matches that of the canonical complex subjects that induce agreement attraction, our results favor the view that the facts Kimball and Aissen brought to our attention, and which have subsequently been analyzed by Kayne (1989) and den Dikken (2001), reflect properties of the real-time processing architecture rather than a structurally-conditioned grammatical process.

The finding that the number of the relative clause head reduces the subject–verb mismatch effect within the relative clause is notable for several reasons. First, the subject–verb mismatch involves a linearly adjacent subject and verb (...*that the reviewer praise*...), and one might expect this configuration to make the mismatch so obvious that other parts of the sentence could have no opportunity to have any ameliorating effects. Second, the relative clause head is not within the immediate structural domain of the subject NP, so feature movement from one to the other, as hypothesized by the feature percolation model, would have to be indirect. Third, despite the fact that the relative clause head attractor was structurally and linearly further from the verb than the attractor in the prepositional modifier paradigm, the reduction of the ungrammaticality effect was of approximately the same magnitude (see Table 11).

Although our demonstration of attraction in this configuration provides important evidence against the percolation model, it does not argue conclusively against models that explain attraction through faulty representation of the subject. A feature percolation model might still be able to explain these findings if the parameters were set correctly; for example, if features could percolate downwards from a number source, and if the distance between the attractor and the subject and between the subject and the verb were weighted fairly low, the differences in distance between the two constructions would not predict large differences in the magnitude of the RT effect. The challenge in pursuing this approach is to make sure that distance is still weighted high enough that it can account for the structural distance effects found in production studies, one of the key motivations for feature percolation models in the first place.

In the case of relative clause processing, there is another potential source for feature confusion, which stems

from the active completion of the filler-gap dependency that is built between the phrase containing the relative clause head and relative clause verb (Frazier & Flores D'Arcais, 1989; Stowe, 1986; Traxler & Pickering, 1996). Attraction inside relative clauses could thus be brought about by a different mechanism from attraction in prepositional-modifier constructions. One might suppose that the relative clause head is reactivated at the RC verb position in the same time frame as agreement is checked, and that features that are simultaneously co-active are liable to interference, or confusion (cf. Clifton et al., 1999; Franck et al., 2006). This view shares the crucial property of the standard feature percolation accounts (developed for complex subject NPs) in predicting symmetrical effects of attraction for grammatical and ungrammatical agreement alike, which we failed to find. An alternative means of capturing these facts, which we discuss in more detail below, is to assume that the attractor exerts its effect by means of a cue-directed retrieval in content-addressable memory.

Timing of agreement effects in self-paced reading

In the six self-paced reading experiments presented above, effects of subject–verb mismatch and attraction sometimes appeared on the verb itself and sometimes on the following word, even when reading times were corrected for the residual effect of reading times on previous regions. In Experiments 1 and 4, effects of mismatch and attraction were observed in reading times on the verb itself, while in Experiments 2, 3, and 5, effects of mismatch and attraction were observed in reading times only on the regions following the verb. One property that may be responsible for this variability in timing is the inclusion of an adverb in the region preceding the verb: Experiments 1 and 4 were the two experiments in which we included an adverb region to serve as an index of effects due to the number of the preceding noun. The pattern we observe suggests that the inclusion of the adverb also may have had the unexpected effect of causing effects of verb number to show up earlier than otherwise. We hypothesize that the occurrence of an adverb may strongly increase expectation for the upcoming verb, such that relationships that depend on the verb can be processed more quickly when the verb is actually encountered. Thus, although including an adverb region can be a useful tool for identifying the existence of effects prior to the verb, our results

Table 11

Grammaticality and attraction effects in region following verb. Region of interest is one region beyond the critical verb. Confidence interval of 95% lower and upper bounds presented within parentheses. 'Baseline' denotes experiment-wide average reading time per word. Pooled standard deviation is computed only over the region of interest.

Exp.	Baseline (ms)	Pooled s.d. (ms)	Effect		
			Grammaticality (ms)	Attraction (ms)	
				Grammatical	Ungrammatical
1	401	184	115 (86, 144)	–	–
2	317	174	62 (39, 84)	–8 (–30, 16)	–49 (–80, –16)
3	340	175	68 (45, 94)	9 (–15, 35)	–34 (–70, –1)
4	312	127	53 (33, 69)	10 (–11, 26)	–45 (–70, –17)
5	327	149	100 (80, 122)	8 (–14, 31)	–63 (–92, –33)
6	309	126	–	1 (–16, 18)	–

suggest that the presence of an adverb can exert effects of its own, which researchers must be aware of.

Lack of attraction in grammatical sentences

The lack of attraction in grammatical sentences is problematic for all models that claim that attraction in comprehension is due to changes in the structural representation of the subject. As discussed in the Introduction, any account in which features from other nouns can spread to the head noun or subject node predicts that this faulty percolation should occur in grammatical and ungrammatical sentences equally, because the percolation mechanism applies independently of the properties of the verb. The same prediction is shared by any syntactic account that assumes that the attractor noun makes itself visible to the agreement system independently of the verb; for example, Den Dikken (2001) proposes that in complex subjects a noun phrase contained within the subject moves to a position that c-commands the subject as a species of generalized quantifier raising. However, in all six attraction experiments, we never found an attraction effect in the grammatical sentences that was comparable to the ungrammatical sentences. Table 11 directly compares the effects of subject–verb grammaticality and attraction across all the self-paced reading experiments and shows the same asymmetrical pattern, with fairly similar values, in each.

Pearlmutter and colleagues (1999) did show attraction effects for grammatical sentences in three experiments using materials that were almost identical to our Experiment 5. Their Experiment 1 using self-paced reading showed a pattern similar to our Experiment 5: they found the predicted symmetrical attraction effect (ungrammatical faster with a plural attractor, grammatical slower with a plural attractor) only in the region following the verb, but in the verb region itself they found a main effect of local noun number (plurals read more slowly) in both ungrammatical and grammatical sentences. Thus, although the grammatical conditions continued to differ in the regions following the verb, the presence of the same difference in the preceding region provides a basis for the alternative interpretation that this difference represents an extended number effect. Pearlmutter et al.'s Experiment 2 used the same materials but with eye-tracking fixation times as the dependent measure. In the first pass measures they found a more puzzling pattern. There were no effects in the verb region, in the first post-verbal region reading times were much faster in the grammatical singular attractor condition than in the other three conditions, and only in the second post-verbal region did a small attraction effect for ungrammatical sentences appear. These results are hard to compare with our own, since we consistently find large attraction effects in the first post-verbal region in ungrammatical sentences, but one possibility is that the unexpected pattern in their first post-verbal region reflects an interaction between the cost of processing plurals and the reduction of disruption due to ungrammaticality in the ungrammatical attraction condition. The results of their Experiment 3, which tested only grammatical sentences, are the most difficult to attribute to a plural com-

plexity effect, since the critical verb region showed an effect of attractor number in only one of the experimental pairs. However, other aspects of the Experiment 3 results are also hard to explain under any traditional agreement account, as they also found a reverse attractor number effect for plural subject sentences, which are not normally subject to any form of agreement attraction (Pearlmutter, 2000, shows a similar pattern).

Several studies have examined agreement processing in comprehension using offline measures and have found reliable attractor effects in grammatical sentence pairs (e.g., Nicol et al., 1997; Häussler & Bader, 2009). Although we failed to show a grammatical attraction effect in our speeded acceptability judgment task, in our Experiments 4 and 5 comprehension question accuracy did show a significant attractor effect in grammatical sentences, although the effect was small. While it seems less likely that the increased complexity of plurals would result in processing costs that extend to the end of the sentence, it is possible that late processes like semantic integration of the subject and the predicate might be sensitive to pure number effects (although a control experiment by Nicol et al., 1997 suggests that noun number could not have been solely responsible for their results). Another possibility is that some offline tasks might engender some sort of late reprocessing or regeneration of the surface form of the sentence, with the result that both grammatical and ungrammatical agreement might become susceptible to the same kind of interference discussed above for production (cf. Potter & Lombardi, 1992).

Although we cannot currently provide a complete account for the previous experiments that have shown online grammatical attraction effects, we were unable to replicate these effects across five self-paced reading experiments using two separate constructions, and we would argue that the cost of processing plural nouns per se that we repeatedly observed in these experiments makes it difficult to unambiguously interpret the existing findings of grammatical attractor number effects in prepositional-modifier constructions. In comparison, the reduction of disruption in ungrammatical sentences is robust and relatively consistent in its time course across different studies and configurations. Although further replication is needed, we argue that this contrast already provides a strong argument against theories that predict symmetrical attraction effects in grammatical and ungrammatical sentences.

Retrieval-based mechanisms for attraction in comprehension

Based on the two lines of evidence outlined above, we have argued that agreement attraction effects in comprehension are not driven by a property of the structural representation of number in the subject itself. We propose that such effects are due to properties of a content-addressable retrieval mechanism that is initiated by the verb. The fact that only sentences in which subject and verb number mismatched showed a reliable attractor effect suggests that information from the verb (or auxiliary) plays a necessary role in attraction effects online. A content-addressable-retrieval mechanism that uses the information on the verb could naturally give rise to the

observed pattern of attraction (Gillund & Shiffrin, 1984; Lewis & Vasishth, 2005). The core idea behind such a retrieval mechanism is that features in the current input are used as cues to query the contents of memory simultaneously, much like keywords are used in Internet search engines to find matching websites. The results of such a query could match all keywords or only a subset of them, and this degree of match may affect the likelihood of retrieving the results from memory.

Retrieval processes could play a role in agreement processing in two different ways: (1) normal agreement processing could be instantiated by a cue-based retrieval process in which verb number is used as a cue to search for the subject in memory; (2) a mismatch between the verb and subject number could initiate a reanalysis process that makes use of cue-based retrieval to find a matching antecedent to fix the mismatch problem. In other words, the subject's number feature is either always retrieved during verb processing, or it is triggered by an error signal. We discuss each of these possibilities in turn.

One way to capture the pattern of effects observed in these comprehension experiments is to assume that subject–verb agreement is always computed through a cue-based retrieval process that is engaged when the verb is encountered (Lewis & Vasishth, 2005; McElree, 2006). Numerous sources of information provided by the verb may form the cues for retrieval. For the configurations we have considered, we assume that the retrieval cues consist of (privately specified) agreement features, like [Number:PI], structural cues, like [Case:Nominative] or [Role:Subject], and clause-bounding cues. The crucial property that is needed for this kind of model to capture the ungrammatical–grammatical asymmetry in attraction effects is that a partially-matching NP is (almost) never retrieved if a fully-matching NP is present. If cue combination rules are supra-linear, a standard feature of content-addressable memory models (Gillund & Shiffrin, 1984; Hintzman, 1988, *inter alia*), then full matching constituents will strongly out-compete partial matches. Alternately, the system may ignore weakly selective superordinate cues like [Category:NP], which apply to multiple constituents. In this way the system would almost always retrieve the correct, number-matching subject in the grammatical sentences, so there is little chance of retrieving another non-number-matching NP in the wrong structural position. On the other hand, when neither of the NPs matches the combined cue, as in the ungrammatical sentences, the number-matching non-subject is sometimes the best match. Wagers (2008) provides an extensive discussion of the possible cue structures that can capture the pattern of results we observe.

The other possibility is that the attractor effect in comprehension is specifically a reanalysis effect. On this view, agreement computation is always carried out correctly on the first-pass, but when this computation fails a reanalysis mechanism can check back to see if an error was made. The initial computation could be instantiated as a predictive process: when a subject NP is encountered, a verb marked with the correct agreement features can immediately be predicted. When the verb is encountered its number features can be checked against the predicted features, and

if they match, nothing more needs to be done; in particular, there is no need to retrieve material from the prior context. However, if the bottom-up features of the verb mismatch the top-down predicted features, then a cue-based-retrieval may be deployed to check whether the correct feature was somehow missed in the syntactic context during the first pass. It is in this 'rechecking' stage that the attractor NPs might sometimes be mistakenly retrieved. The fact that attractor effects are mainly seen in ungrammatical sentences is thus a natural consequence of this view.

The data presented here do not choose between these options and each has benefits and drawbacks. Either account relies on a cue-based retrieval for the number information in the subject. The accounts diverge on the issue of whether that retrieval occurs whenever the verb is processed or if the retrieval is limited to cases where the expectation for the verb's number marked is unmet. On the one hand, there are several reasons to favor an account that limits retrievals to instances of reanalysis. First, it makes retrieval of the number feature unnecessary in the normal case. Second, given that English agreement paradigms for lexical verbs are largely syncretic, it may be necessary in the first place to use top-down information, like the number of the subject head, to identify the number features of the verb. Finally, McElree et al. (2003) concluded on the basis of speed-accuracy tradeoff time-course dynamics that adjacent subjects and verbs can simultaneously occupy the focus of attention. As a consequence, they can be integrated without necessitating a retrieval. We observe in Experiment 2 and 3 that adjacent subjects and verbs are nonetheless liable to attraction when subject and verb mismatch. The existence of agreement attraction effects in adjacent subject–verb sequences can be reconciled with the focus of attention findings if no number retrieval is required unless there is an error signal. On the other hand, there are potential costs involved in making the prediction assumed in the alternative account, depending on the implementation. For example, it may not be possible to maintain the expected verb feature while intervening material is being processed (e.g., while the PP is being attached in N-PP structures), such that a retrieval should usually be necessary. Finally, it is worth noting that the two alternative accounts can be viewed on a continuum: whether top-down vs. bottom-up processes predominate may depend on precise characteristics of the constituents and structures involved. Further research will be necessary to disentangle the interaction between prediction and retrieval.

The scope of interference

We have offered a unified analysis of PP and relative-clause agreement attraction in terms of retrieval-based interference. This unification is based on similar patterns of attraction involving singular/plural markedness and also the grammatical/ungrammatical asymmetry. However, there may still be differences between the two structures. Bock and Miller (1991) found that in a production study involving relative clause preambles the majority of errors occurred for singular embedded subjects when the relative

clause head was plural and, crucially, animate. This finding contrasted with N–PP preambles, in which the animacy of the local noun did not affect rates of attraction. This production contrast might motivate distinguishing the two constructions, such that comprehenders are genuinely confused about the identity of the subject in relative-clause attraction but not in PP attraction. Our findings resist this distinction in one respect: the fact that attraction only occurs for ungrammatical strings implies that comprehenders are not generally uncertain about the relative clause subject. If they were, the pattern of RTs would be similar to that predicted by the percolation account. In a similar vein, Wagers (2008) found that relative-clause attraction in ungrammatical strings was present both when the relative clause was attached to a main clause subject and when it was attached to a main clause object. This finding provides further evidence that attraction in comprehension is not contingent upon how ‘subject-like’ the attractor is.

However it seems reasonable that comprehenders could become uncertain about the identity of the subject after detecting a subject–verb mismatch. To put this more generally, satisfying the agreement requirements of the verb with a grammatically-inappropriate head could lead to realignment of the grammatical relations closely related to agreement, like subject-hood or conceptual number. In some recent research, our group has found no evidence that attraction leads to reassignment of grammatical roles (Lau, Wagers, Stroud, & Phillips, 2008) or conceptual number (Lau, Wagers, & Phillips, 2009) for N–PP attraction in comprehension. However the effects of attraction on the interpretation may be more subtle. We believe that investigating this question is an important future area of research, not only to provide a better account of agreement attraction but also to provide a better understanding of the role retrieval plays in assembling combinatorial representations. In particular, determining whether or not it is possible to retrieve and process some features independently of others could shed light on the granularity of the constituent encodings that support comprehension.

Production vs. comprehension

What is to be made of the link between comprehension and production? One attractive aspect of the feature percolation model is that it can be easily stated independently of the task, because the error derives from the syntactic encoding itself. Consequently, the explanation for agreement attraction in comprehension and production is fundamentally the same. It is less clear that a model based on retrieval has the same extensibility, but we would like to argue that it does. Following ideas in Solomon and Pearlmuter (2004), we suggest that the key element that speech planning and retrieval in comprehension share is that they are sequence management tasks in which elements may be simultaneously active. In Solomon and Pearlmuter (2004)’s model of agreement in production, what drives the attraction effect is the simultaneity of the head nouns during the production planning process. The attractor can wrest away control of agreement by being co-active with the grammatical controller when con-

ceptual structure is mapped onto syntactic structure. Because both heads are simultaneously accessible, the process of selecting the correct verb form sometimes spuriously pays attention to the attractor’s features. The more accessible the attractor, the more likely it is to be spuriously selected. In their model simultaneity is determined by the tightness of the semantic relation between heads: roughly, the degree to which the attracting head characterizes the subject head. In the comprehension model proposed here, simultaneity again plays a role. Because retrieval of constituents is cue-driven and not serial, there is a possibility that multiple constituents will be rendered accessible to comprehension processes. The choice of which set of constituents is made accessible depends on the match between the retrieval cues and constituent features.

Recent theoretical work by Badecker and Lewis in the ACT-R framework (2007), and recent empirical work by Badecker and Kuminiak (2007) on gender attraction in Slovak, has sought to explain production errors of agreement in nearly exactly the same fashion that we are using to explain the comprehension errors: attraction arises when cue competition leads to a partial match. The production process is posited to take place in the same kind of architecture as comprehension, one in which most operations must retrieve information from recent memory. Verb marking occurs after the subject has been constructed, and it must retrieve the subject to inspect its number properties. Both the subject phrase and the embedded attractor share a category feature, as well as a nominative case feature (in the planning process). The whole subject is distinguished from the embedded attractor because its dominating category is also encoded. Therefore a set of cues exists that will converge upon the whole subject, but will also partially activate the local noun. Consequently the production system retrieves the whole subject in the majority of cases. Embedded plurals lead to attraction to a greater extent than embedded singulars because the cue structure includes a variable value cue: Num:var. The system is thus biased to return explicitly number marked constituents. The proposal by Badecker and Lewis is compatible with either of our accounts for comprehension, because both of our accounts attribute the attraction effect to similarity-based interference grounded in the feature composition of related constituents. Although there is no clear analog of reanalysis in production, in our view reanalysis is simply one of many factors that govern the timing of the retrieval operations that are common to both production and comprehension.

In either Solomon and Pearlmuter (2004), Badecker and Lewis (2007), or our own account of comprehension, the encoding of nominal number is assumed to be accurate but the process of accessing a number feature is error-prone. The question then arises whether the structural distance effects found in production have an analog in comprehension, and if so, what account can be given. Pearlmuter (2000) provides some evidence for distance effects in comprehension from self-paced reading experiments involving stacked PP modifiers. The evidence is somewhat equivocal, as those results do not replicate the plural markedness effect and are subject to our more gen-

eral concerns over the processing costs of plurals. However, assuming that hierarchical effects do hold in comprehension, we propose the explanation must be found in patterns of access. In production, Badecker and Lewis provide one mechanism for hierarchically modulating access to constituents in terms of activation: hierarchically more dominant categories have higher base rates of activation, because they have undergone more processing (i.e., more modification). Higher rates of activation are proposed in their framework, ACT-R, to lead to higher retrieval likelihood. It is possible to posit a similar mechanism in comprehension (Lewis & Vasishth, 2005). Some caution must be observed since modulation of activation, as a function of processing depth, will only heuristically and imperfectly recapitulate hierarchical order. However at present we would simply emphasize the need for more work in comprehension, in order to better sample the logical space of subject head and attractor configurations.

Plural complexity effects in self-paced reading

Our reading time data add to a growing body of evidence that factors known to impact lexical decision times – in this case, the effect of noun number – are also relevant in the self-paced reading technique (Niswander, Pollatsek, & Rayner, 2000; Bertram, Hyönä, & Laine, 2000; Lau et al., 2007). In Table 12 the effect of reading the plural attractor is compared to its singular counterpart in each of the six experiments, analyzed one region downstream. There is a consistent elevation of reading times in the plural condition. The size of the effects varies across the different experiments, which may be due to differences in structure, ordinal position, and participants. In particular, the effect in Experiment 1 was much larger numerically than in the other experiments and previous self-paced reading studies, perhaps because of the increased variability and longer reading times seen for this study, or perhaps because of the increased anticipation for the noun created by the prenominal adjective included in these materials. However, within the experiments that used the same structural environment (i.e., relative clauses in 2 and 3; complex subjects in 4–6), the effect size was fairly consistent. More work is needed to determine whether the plural cost is due to morphological processing, semantic integration, length, or some other factor.

It is important to note that controlling for length by means of a residual reading time analysis is insufficient

Table 12

Effect of plurality in region following the attractor. Region of interest is one region beyond the attractor noun. Confidence interval of 95% lower and upper bounds are presented within parentheses. Baseline denotes experiment-wide average reading time per word. Pooled standard deviation is computed only over the region of interest.

Exp.	Baseline (ms)	Pooled s.d. (ms)	Plurality effect (ms)
1	401	201	57 (21, 100)
2	317	159	11 (–0.1, 23)
3	340	105	9 (2, 16)
4	312	134	19 (3, 36)
5	327	124	14 (3, 26)
6	309	162	15 (–4, 37)

to control for increased plural reading times. First, as Table 12 demonstrates, the effect is persistent and shows up in reading times on the subsequent word, which are otherwise matched for average word length. Second, the size of the effect is larger than the typical millisecond-per-character slopes that we observed in by-participant regressions in this data set and across a broad range of unrelated studies—namely around 3–7 ms per character. Since the length difference between singulars and plurals is only one character for regular nouns, correction of reading times based on a word length regression should shrink the difference between the two forms by only 3–7 ms. In contrast, the previous-region-RT covariate analysis we presented for Experiments 4 and 5 seems to provide a satisfactory means of controlling for extended complexity effects (cf. Vasishth, 2006).

Conclusion

We have demonstrated properties of agreement attraction in comprehension that are inconsistent with accounts in which attraction effects are driven by the erroneous representation of subject number. A relative clause configuration in which the attractor was hierarchically superior to the subject and did not intervene between subject and verb showed strong attraction effects. Number marking on non-subject nouns had a large and robust impact on processing ungrammatical agreement, but no effect on processing grammatical agreement. These findings suggest that the representation of subject number is not influenced by the mere presence of nearby nouns with conflicting number. We conclude that attraction errors reflect how structure-building processes gain access to information during the course of comprehension or production and, in particular, are consistent with a cue-based retrieval mechanism for accessing and comparing previously processed constituents.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jml.2009.04.002.

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