Agreement errors are predicted by rational inference in sentence processing

Rachel Ryskin¹, Leon Bergen², and Edward Gibson³

1. Cognitive & Information Sciences, University of California, Merced
2. Linguistics, University of California, San Diego
3. Brain and Cognitive Sciences, Massachusetts Institute of Technology

Please address correspondence to Rachel Ryskin. E-mail: rryskin@gmail.com

Abstract

People are able to understand language in challenging settings which often require them to correct for speaker errors, environmental noise, and perceptual unreliability. To account for these abilities, it has recently been proposed that people are adapted to correct for noise during language comprehension, via rational Bayesian inference. In the present research, we demonstrate that a rational noisy-channel framework for sentence comprehension can account for a well-known phenomenon—subject-verb agreement errors (e.g. *The key to the cabinets are...*). A series of experiments provides evidence that: a) agreement errors are associated with misrepresentations of the sentence consistent with noisy-channel inferences and b) agreement errors are rationally sensitive to environmental statistics and properties of the noise. These findings support the hypothesis that agreement errors in production result in part from a sentence comprehension mechanism that is adapted to understanding language in noisy environments.

Introduction

In everyday communication, people typically understand language effortlessly despite the fact that the linguistic signal can be corrupted in many ways. For example, listeners successfully correct for the phonological and syntactic errors of young speakers, non-native speakers, speakers under duress, and speakers with language impairments; they can suppress ambient noise (e.g., during conversations at a cocktail party); and they can adjust to the visual distortions of a rapidly changing environment (e.g., reading road signs while driving on a highway). To account for these abilities, it has recently been proposed that people are adapted to understand language in the presence of noise (Shannon, 1948; Aylett & Turk, 2004; Levy, 2008; Levy, 2011; Gibson, Bergen & Piantadosi, 2013). According to such noisy-channel models, listeners correct for noise in a rational manner, integrating both their prior expectations about what meaning was intended and their knowledge of what types of noise are most likely in their environment.

Prior work has shown that listeners infer the intended meaning of a sentence when the content of the linguistic input is semantically implausible (Gibson, Bergen, & Piantadosi, 2013; Gibson et al., 2017). Here, we investigate a new source of evidence for the claim that sentence processing is rational: errors in syntactic analysis. We begin by introducing the noisy channel framework for sentence processing. We then briefly review the literature on syntactic agreement and lay out predictions of the noisy channel model for agreement errors. Traditional models of agreement errors have focused on production (e.g., Eberhard, Cutting, & Bock, 2005; Mirković & MacDonald, 2013) or memory-retrieval (e.g., Wagers, Lau, & Phillips, 2009) mechanisms. Here we propose

that comprehension-side pressures—rational inferences over a noisy channel—contribute to explaining existing behavioral patterns in the agreement error literature.

The Noisy Channel Framework

The noisy-channel framework proposes that listeners rationally integrate their expectations about the intended meaning of a sentence with their knowledge of the noise process that may have corrupted that sentence. This process of decoding the language input can be posed in terms of optimal Bayesian inference. The comprehender's prior model of the language can be represented by a probability distribution P_L , which is defined over phrases or sentences. This takes into account the comprehender's expectations about what the speaker is likely to say—incorporating both linguistic and world knowledge. The model of the noise process is given by the distribution P_N . This distribution specifies what kinds of noise the comprehender expects (e.g., the deletion of a letter in the perception of the input, or the accidental insertion of a morpheme by the speaker). By Bayes' Rule, the probability that a sentence or phrase s_i was intended given the perceived sentence or phrase s_p is equal to:

$$(1) \quad P(s_i | s_p) = \frac{P_L(s_i)P_N(s_i \rightarrow s_p)}{P(s_p)}$$

where $P_N(s_i \rightarrow s_p)$ is the probability that s_p will be perceived when s_i is intended by the speaker: the likelihood that noise corrupted s_i into s_p .

This framework is consistent with previous modeling work and experimental studies that have provided evidence for the effect of a noise-correction process on sentence comprehension. Levy (2008) proposed a Bayesian model of noisy-channel sentence comprehension similar to the present one, and suggested that such models might

shed light on a number of syntactic comprehension phenomena difficult to reconcile with traditional sentence-processing models. Gibson, Bergen, & Piantadosi (2013) provided evidence that, when the literal meaning of a sentence is a priori implausible (e.g., *The mother gave the candle the daughter.*), comprehenders infer that the true intended meaning corresponds to a close alternative (e.g., *The mother gave the candle to the daughter.*). Further, there is evidence that comprehenders can be induced to disregard punctuation (commas) in reading on the basis of strongly biased grammatical expectations, and to adopt a garden-path syntactic analysis that should be incompatible with the actual orthographic material (Levy, 2011). For example, in the sentence “*As the soldiers marched, toward the tank lurched an injured enemy combatant.*” despite the presence of the comma, readers interpret *toward the tank* as a dependent of the subordinate-clause verb, *marched*, and experience processing difficulty at the main-clause verb, *lurched*. This incorrect analysis is rational given the low probability of the locative inversion construction, *toward the tank lurched an injured enemy combatant*. Similarly, readers can entertain the possibility that a previous word was misrecognized on the basis of alternative syntactic analyses of an input prefix (Levy, Bicknell, Slattery, & Rayner, 2009). Finally, Bergen, Levy, and Gibson (2012) show that comprehenders rationally misidentify low-probability constructions as more high-probability alternatives. In a sentence completion task, readers often completed the low-probability preamble (e.g., Noun-Noun phrase: *The immigrant fear...*) in an ungrammatical way (e.g., *...being deported*) reflecting a noisy representation of the preamble (e.g., possibly as the higher probability preamble Noun-Verb phrase: *The immigrants fear*). Furthermore, online reading time measures demonstrate that these misidentifications have downstream

processing consequences. Comprehenders adopt these alternative syntactic interpretations as they process the remainder of the sentence and find themselves garden-pathed when they encounter evidence that the literal interpretation of the written sentence had been correct and their rationally inferred alternative parse was incorrect.

The finding that comprehenders appear to account for the possibility of noise in their input by entertaining alternative syntactic representations suggests a parsimonious explanation for a different, well-attested psycholinguistic phenomenon: subject-verb agreement errors (e.g., Bock & Miller, 1991). The production of sentences with incorrect number agreement (e.g., *The key to the cabinets were lost.*) may be the result of a noisy representation of the number marking of the sentence preamble (*The key to the cabinets...*) and the existence of a higher-probability alternative (e.g., *The keys to the cabinets...*). This account is particularly pertinent in settings where the agreement production is prompted by the comprehension of a preamble, though it may have broader implications for agreement errors that occur in conversation where interlocutors switch frequently between comprehending and producing, often mid-sentence. In the present research, we will extend the prior work on rational noisy-channel sentence comprehension and apply these principles to explain patterns of syntactic agreement errors.

Models of Syntactic Agreement Errors

Agreement errors have traditionally been viewed as failures of sentence production, and, as such, have been used by psycholinguists to study the mechanisms involved in sentence production. In a common elicitation task (e.g., Bock & Miller,

1991), experimental participants are presented with an initial sentence fragment such as *The key to the cabinets*, and they are asked to repeat the segment and continue it as a complete sentence. Errors that participants make in this paradigm have been provided as evidence for how the sentence planning mechanism integrates syntactic constraints across different parts of the sentence.

The most basic finding in agreement-error elicitation studies is that agreement errors are most likely to occur when the head noun (*key*) is singular and the local noun (*cabinets*) is plural, as in *The key to the cabinets are* Agreement errors rarely occur for the other three combinations of number marking for comparable initial segments, including, perhaps surprisingly, the plural-singular combination (e.g., *The keys to the cabinet is ...*). One class of accounts explains these errors as resulting from errors in hierarchical feature-passing: number features are passed up a sentence's syntactic tree, and agreement errors occur when number features are incorrectly propagated through the tree (Vigliocco & Nicol, 1998; Hartsuiker et al., 2001; Franck et al., 2002; Eberhard et al., 2005). Critically, in order to account for the observed asymmetry between singular-singular and plural-singular error elicitations, it is assumed that there is an asymmetry in the "markedness" of different noun endings (such that singular nouns are unmarked, and plural nouns are marked).

A second class of accounts views agreement errors as resulting not from errors in syntactic computation but rather from memory encoding or retrieval errors at the interface between the sentence production system and memory (Solomon & Pearlmuter, 2004; Badecker & Kuminiak, 2007; Haskell & MacDonald, 2003; Wagers, Lau, & Phillips, 2009). For instance, Wagers et al. (2009) propose that, as a verb is processed,

morphological cues are deployed to retrieve the subject. Interference may arise when multiple candidate subjects provide a match to the cue features. The asymmetry in agreement errors rests on the assumption that memory cues contain a variable that marks grammatical number and that the plural is “marked” relative to the singular.

Recently, attempts have been made to reconcile these two accounts by positing that models like Marking and Morphing (Eberhard et al., 2005) explain production agreement patterns better, while cue-based retrieval (Wagers et al., 2009) may play a larger role in comprehension (Tanner, Nicol, & Brehm, 2014). To further attempt to delineate these accounts, Patson & Husband (2015) probed the comprehension of sentences used to elicit agreement difficulties in comprehension (e.g., *The key to the cabinets are on the table*). They argued that Marking and Morphing predicts that the number of the head noun should frequently be misrepresented in the case of the singular-plural noun phrases, while cue-based retrieval makes no such predictions. They found that agreement attraction sentences led to frequent misinterpretation of the number of the items in the head noun phrases (e.g., *Was there more than one key? Yes*) but no relationship between misinterpretations and online reading times. They concluded that neither account, without modification, can account for the full range of results. In line with these findings, we propose that these misinterpretations are indicative of a larger linguistic principle which can parsimoniously explain patterns of agreement in elicitation tasks: that language transmission occurs over a noisy-channel.

Rational inference in the comprehension of syntax

In contrast to more traditional accounts, we propose that the syntactic analysis of a sentence takes place in the context of a rational process by which comprehenders

attempt to infer the speaker’s intended signal given the possibility of noise (Bergen, Levy, & Gibson; 2012; in prep; Levy, 2011; Levy et al., 2009). For example, if the listener perceives an ungrammatical sentence like “The sailor hope the weather will be good.” she may infer that the discrepancy between the singular subject (*sailor*) and plural verb (*hope*) was not intended by the speaker but rather the result of a speech error or auditory misperception. Multiple grammatical sentences could have been minimally corrupted in order to produce this ungrammatical sentence. For example, an –s could have been deleted from “The sailors hope the weather will be good.” or “The sailor hopes the weather will be good.” Thus, it seems rational for the listener to adopt an interpretation of the sentence that doesn’t directly match the perceived input but is minimally different and grammatically correct, such as “The sailors hope the weather will be good.” In other words, the conflict in subject-verb agreement can be resolved by a simple syntactic reanalysis. A noisy-channel view of language processing posits that this type of rational inference is a commonplace occurrence in everyday language processing and can explain myriad patterns observed in psycholinguistic experiments. In what follows we elaborate on the predictions of the noisy channel model and how it can explain certain phenomena in the syntactic agreement literature in particular.

Returning to Equation 1, having perceived the input s_p , we can measure the comprehender’s evidence for one intended sentence s_{i1} relative to another intended sentence s_{i2} by the following ratio:

$$(2) \quad \frac{P(s_{i1}|s_p)}{P(s_{i2}|s_p)} = \frac{P_L(s_{i1})P_N(s_{i1} \rightarrow s_p)}{P_L(s_{i2})P_N(s_{i2} \rightarrow s_p)}$$

The higher this value, the more evidence that s_{i1} and not s_{i2} was intended. In the case of

$s_{i2} = s_p$, where s_p is the perceived sentence, the resulting ratio

$$(3) \quad \frac{P(s_i | s_p)}{P(s_p | s_p)} = \frac{P_L(s_i)P_N(s_i \rightarrow s_p)}{P_L(s_p)P_N(s_p \rightarrow s_p)}$$

can be interpreted as the probability that an error occurred and s_i was intended relative to the probability that no error occurred and s_p was in fact intended. This ratio will be more positive in situations where $\frac{P_L(s_i)}{P_L(s_p)}$ is higher and $P_N(s_i \rightarrow s_p)$ is higher. These formulas capture some key intuitions about how people should infer the intended input:

i) Prior linguistic and world knowledge constrain people's inferences about the speaker's intended meaning. If a particular phrase is very unlikely a priori, then it is even more unlikely that it was intended by the speaker and then altered by the noise¹. Thus, the comprehender may infer the presence of noise when there is an alternative sentence s_i that is sufficiently similar to s_p and has higher probability according to the language model P_L . Formula 3 states that as the ratio $\frac{P_L(s_i)}{P_L(s_p)}$ of the prior probability of s_i relative to s_p increases, the comprehender will be more likely to infer that s_i was intended. This implies that a syntactically incorrect phrase (*The sailors hopes...*), which necessarily has low probability, will lead the comprehender to infer that a syntactically licensed phrase was intended (e.g., *The sailors hoped...*). Furthermore, Bergen et al. (2012) showed that the comprehender will infer that the input was corrupted even when the actual phrase, s_p , is well-formed (e.g., *The immigrant fear...*) if the phrase is highly unlikely because it

¹ Gibson et al. (2013) provide evidence for this at the level of semantic a priori likelihood but here we focus on likelihood of the syntactic structure.

contains a low-probability syntactic construction (e.g., *fear* in a Noun-Noun phrase).

When there is a sufficiently similar sentence s_i that has higher probability under the language model, then the ratio in formula 3 may be high enough for the comprehender to infer that s_i was actually intended, even when s_p is syntactically licensed.

ii) The model of the noise likelihood will constrain whether comprehenders infer that corruption occurred or not. Production errors are more likely to bear some relation to the intended message than not (Dell & Reich, 1981). Similarly, our perception does not introduce random errors into the input; misperceptions are biased towards contextually congruent interpretations (e.g., Samuel, 1981). Consequently, the noise process makes certain hypotheses about how the input might be corrupted very unlikely. If sentence s_i is very different than s_p , then it would require a large number of specific errors to transform s_i into s_p . As a result, $P_N(s_i \rightarrow s_p)$ would be low, and then, by equation 1, the probability $P(s_i | s_p)$ that s_i was intended must also be low. Thus, alternative sentences that are more similar to the perceived sentence will be more likely candidates for the intended meaning of the speaker than dissimilar ones.

As a corollary, the noisy channel model predicts that comprehenders should be more likely to infer that a perceived language unit (e.g., a letter, morpheme, or word) was intended by the speaker than that the absence of a language unit was intended (Gibson et al., 2013). This prediction follows from the Bayesian size principle (Xu & Tenenbaum, 2007; MacKay, 2003), which states that when a hypothesis derives from a large hypothesis space, most individual hypotheses can only received a small amount of probability. This principle can be illustrated by the following distribution:

$$(4) \quad P(h|H) = 1/|H|$$

where H is the hypothesis space containing h , and $|H|$ is the number of possibilities contained in H . As the size of the hypothesis space H increases, the probability assigned to any specific hypothesis h decreases. With respect to a noisily-represented sentence, a word h inserted into a sentence arguably has as its alternatives all possible words in the English language². Thus, the probability of h being inserted is quite small. On the other hand, a word h that is deleted from a sentence has as its alternatives only the other words in that sentence³. Similarly, while there are 26 English letters that could be inserted at a given location, due to perceptual noise, only one letter can be deleted from a specific location. Thus, there is a higher probability that a particular sentence s_{i1} was intended, but a letter was deleted from it, than that another sentence s_{i2} was intended, but a letter was inserted into it.

Rational inference in agreement errors.

Given these constraints, the rational noisy channel framework can straightforwardly explain the basic pattern of agreement errors found in the literature (e.g., *The key to the cabinets are...*). According to this proposal, agreement errors occur when the initial (head) noun is inferred to have an incorrect number marking. The activation of two representations – the (correct) perceived head noun (e.g., *key*), and the (incorrect) inferred head noun (e.g., *keys*) – results in the production of a sentence that combines

² We take all possible words in the English language as a starting point though it is likely that the hypothesis space is constrained by factors such as semantic or phonological relatedness to other words in the sentence, frequency, word class, etc. Nonetheless, this encompasses a much larger set of possibilities than in the deletion case.

³ As a first approximation, we assume that there are two types of relevant noise: insertions and deletions.

their elements: the perceived head noun is used in the repetition of the preamble, while the inferred head noun is used to determine the number marking of the main verb. The noisy-channel framework predicts that comprehenders will be most likely to make incorrect inferences about a noun's plural marking in precisely the conditions that agreement errors are most often observed: when the head noun is singular and the local noun is plural. This prediction can be broken into two parts that are summarized in Table 1:

a) Agreement errors will occur more often when the head noun is singular. In the noisy channel framework, this can be recast as the following prediction: comprehenders will mistakenly infer that a singular head noun is plural more often than they infer that a plural head noun is singular. This is predicted because of properties of the noise likelihood $P_N(s_i \rightarrow s_p)$ and features of English number morphology, which forms the plural by adding “-s” or “-es” to the singular. The insertion of a morphological suffix (or a sequence of letters) transforms a singular noun into a plural noun, while a deletion of a morphological suffix (or a sequence of letters) transforms a plural noun into a singular noun. Comprehenders will mistakenly infer that an observed singular noun is a plural noun if they infer that an ending was *deleted* from the plural noun, and they will infer that an observed plural noun is a singular noun if they infer an *insertion* onto the singular noun.

The noise likelihood $P_N(s_i \rightarrow s_p)$ should assign higher probability to deletions than insertions, consistent with the Bayesian size principle (see ii above). Thus, it is reasonably likely for a plural head noun to be transformed to a singular head noun—a transformation that requires a deletion—while it is unlikely for a singular head noun to be

transformed to a plural head noun—a transformation that requires an insertion. This prediction accords with Stemberger’s (1985) observation that, in a corpus of spontaneous speech errors, the rate of “-s” deletions was 14 times greater than the rate of insertions.

b) Agreement errors will occur more often when the head noun is singular and the local noun is plural than when both the head and local nouns are singular because of properties of the prior distribution (see i above). An analysis of the Switchboard corpus of spoken American English showed that singular-singular prepositional phrases are 3.5 times as frequent singular-plural phrases; 5 times as likely as plural-singular phrases; and 6 times as likely as plural-plural phrases. As a result, it is unlikely that another construction was intended if a singular-singular PP is presented, while it is more likely if a singular-plural PP is presented. Combined with part a), this establishes that agreement errors should occur most frequently for singular-plural constructions. The asymmetry between singular-plural and plural-singular error rates follows naturally from the theoretically predicted asymmetry between deletions and insertions together with a prior bias for singular-singular NP-PP sequences, as observed in corpora. Thus, agreement errors in the standard elicitation task (e.g., *The key to the cabinets are...*) can be in part explained by rational properties of sentence *comprehension*, rather than failures of sentence production.

Head Noun	Local Noun	Errors predicted?	Reason
Plural	Plural	No	Insertions are unlikely
Plural	Singular	No	Insertions are unlikely
Singular	Plural	Yes	Deletions are likely; lower base-rate

Singular	Singular	No	High base-rate
----------	----------	----	----------------

Table 1: Explanation of the noisy channel model’s prediction of greatest errors in the singular-plural condition.

Present research

In addition to explaining the classic pattern of agreement errors found in the literature, the noisy channel proposal makes a series of novel predictions about syntactic comprehension, which we test in the present research. We first replicate the classic patterns observed in agreement error elicitation paradigms (Experiment 1a) and show that, consistent with a rational comprehender account, participants make the most agreement errors when the head noun is singular and the local noun is plural (*The key to the cabinets...*). Additionally, the noisy-channel framework proposes a role for misperception during comprehension in the production of agreement errors. That is, people place an incorrect number marking on a sentence’s verb when they have misperceived the sentence’s preamble. If people are misperceiving the sentence preambles, then they should produce *repetition errors*, in which both the verb and the preamble receive incorrect number markings. For example, if people misperceive *The key to the cabinets* as *The keys to the cabinets*, then they should produce completions like *The keys to the cabinets were in the kitchen*. Moreover, if repetition errors have the same source as agreement errors, they should pattern with agreement errors: they should occur most often for singular-plural preambles, and less often in the other conditions. Indeed, we see that, in Experiments 1a-c, the repetition errors made by participants when typing the preamble reflect a noisy-channel inference process.

The noisy-channel framework also predicts that reducing the likelihood of noise (see ii above) and increasing the prior probability of infrequent constructions (see i above) decreases the rate of inferences. Indeed, participants make fewer agreement errors when the likelihood of misperception is reduced through additional time to read the preamble (Experiment 1b), or when they are provided with more cues to the correct number marking of the head noun, whether through the presence of an indefinite article (*A key to the cabinets*; Experiment 2) or a relative clause (*The professor that is teaching the classes* versus *The professor teaching the classes*; Experiment 3). Similarly, manipulating the prior probability of the preamble, by increasing the rate of singular head nouns in the experimental context (Experiment 1c), led to a decrease in agreement errors.

Experiment 1a

The aim of Experiment 1a was to replicate the classic findings of Bock & Miller (1991) in a visual presentation paradigm. Whereas previous studies usually used audio presentations and/or spoken responses, the presentations in our paradigm were visual and the responses were typed. Participants were presented with visual sentence preambles and asked to re-type these preambles and complete them. This paradigm was used in order to allow us to manipulate the task requirements in later experiments and to closely examine repetition errors.

Methods

Participants. We recruited 79 participants from Amazon's Mechanical Turk, a service which can be used for collecting behavioral data over the internet (Gibson & Fedorenko, 2013). Participants were restricted to those with IP addresses located in the

US. One participant did not provide responses for all critical trials but data from any trials they completed was included.

Materials. We constructed 32 items of the form *The Noun Prepositional Phrase*, e.g. *The key to the cabinets*. Sixteen of these sentence preambles were taken from Bock & Miller's original set. The plural marking of the head noun (*key*) was crossed with the plural marking of the local noun (*cabinets*), resulting in four conditions. The materials were presented in a Latin-square design. In addition, 48 filler items of the form *The Noun*, e.g. *The boy*, were randomly interleaved with the experimental items. Half of the fillers contained a singular noun and half contained a plural noun.

Procedure. Participants were shown each sentence preamble for 1.5 seconds. The preamble then disappeared from the screen, and participants were given 13 seconds to retype the preamble and complete the sentence.

Coding. For all analyses, responses were divided into three categories. A response was categorized as *correct* if the sentence preamble was repeated correctly, and the response contained a grammatical independent clause continuing this preamble; the main verb in the continuation may have had either a correct, unambiguous number marking or an ambiguous number marking. A response was categorized as an *agreement error* if the sentence preamble was repeated correctly, and the number marking of the continuation's main verb did not agree with the head noun of the preamble. Responses were coded as repetition errors when the head noun and verb were completed with incorrect number markings (e.g., if *The key to the cabinets* is completed as *The keys to the cabinets were...*), but the sentence was otherwise correct. Finally, a response was

categorized as a *miscellaneous error* if the sentence preamble was repeated incorrectly, or the response did not contain a grammatical independent clause (repetition errors were included in miscellaneous errors for the purposes of the analysis of agreement errors). Responses were not categorized as miscellaneous errors on the basis of minor spelling mistakes.

Results

Agreement Errors. Across the whole experiment, 14% of trials contained an error of any kind (including misspellings), 4% contained an error on the preamble, and 3% of responses were coded as containing a verb agreement error. Excluding trials with miscellaneous errors or errors on the preamble, 4.4% of all trials contained agreement errors. The highest proportion of agreement errors (12.3%) was observed in the singular-plural condition. Agreement errors occurred less than 2.5% of the time in all three other conditions. A summary of the proportions of agreement errors is shown in Figure 1.

Following standard practice for analyzing binary data with averages close to the boundary (0%), we used weighted empirical logit regressions (Barr, 2008; Gillespie & Pearlmutter, 2013) to perform all analyses reported in this paper. Because there is not a consensus about how best to analyze this type of data, the reported comparisons were validated using logistic mixed effects models. The results from these mixed effects models are only reported when they differ from the empirical logit regressions. All models are available in the Supplementary Material.

Number of the head noun (singular vs. plural) and number of the local noun (singular vs. plural) along with their interaction were entered as deviation-coded predictors. The head noun's number marking significantly predicted the rate of agreement

errors (by-subjects: $\beta=0.28$, $SE=0.09$, $t=3.07$, $p<0.005$; by-items: $\beta=0.38$, $SE=0.14$, $t=2.63$, $p<0.01$)⁴, such that participants made more agreement errors when the head noun was singular. The local noun's number marking also significantly predicted the rate of agreement errors (by-subjects: $\beta=-0.47$, $SE=0.09$, $t=-5.06$, $p<0.001$; by-items: $\beta=-0.60$, $SE=0.14$, $t=-4.20$, $p<0.001$), such that participants made fewer agreement errors when the local noun was singular. There was also a significant interaction between the head noun and local noun (by-subjects: $\beta=-0.92$, $SE=0.18$, $t=-5.02$, $p<0.001$; by-items: $\beta=-1.32$, $SE=0.29$, $t=-4.62$, $p<0.001$), with agreement errors occurring most frequently with a singular head noun and plural local noun.

Repetition Errors. Repetition errors on the head noun occurred on 3% of all trials. Repetition errors on the local noun occurred on 0.2% of all trials so we do not examine these cases further. Head noun repetition errors on trials with correct verb agreement occurred in 6% of the responses in the singular-plural condition, twice as often as any of the other conditions. Empirical logit regressions revealed a significant main effect of the local noun (by-subjects: $\beta=-0.34$, $SE=0.08$, $t=-4.37$, $p<0.001$; by-items: $\beta=-0.59$, $SE=0.15$, $t=-3.91$, $p<0.001$) and a significant interaction between the head and local noun (by-subjects: $\beta=-0.56$, $SE=0.16$, $t=-3.63$, $p<0.001$, by-items: $\beta=-0.91$, $SE=0.30$, $t=-3.00$, $p<0.005$).

Discussion

Our online, typing paradigm replicates the effects from Bock & Miller's original paper: participants are more likely to produce an agreement error when the head noun is

⁴ The effect of head noun number does not reach significance in the logistic mixed-effects analysis ($\beta=0.60$, $SE=0.37$, $t=1.60$, $p=0.11$).

singular and the local noun is plural than when the head noun is plural and the local noun is singular. The asymmetry is consistent with multiple accounts (e.g., Eberhard et al., 2005; Wagers et al., 2009) including the noisy-channel framework which proposes that errors are most likely in the singular-plural case because an -s is likely to be deleted during noisy transmission and singular-plural phrases are infrequent.

The classic singular-plural mismatch effect for agreement errors is also found for repetition errors, consistent with the claim that people are misperceiving the sentence preambles. The latter result is not predicted by either memory-retrieval accounts or feature-passing accounts, which have assumed that there are no errors in the representation of the preamble itself.

Figure 1. Proportion of agreement errors by preamble condition in Experiments 1a-c.

Error bars represent standard error of the mean.

Figure 2. Proportion of repetition errors by preamble condition for Experiments 1a-c.

Error bars represent standard error of the mean.

Experiment 1b

Experiment 1b tested a second prediction of the noisy-channel framework: that decreasing the noise rate in the task should decrease the rate of agreement errors. If the noise rate is decreased, then the observed preamble would be less likely to have been accidentally produced by an alternative preamble. Lowering the noise rate is equivalent in Equation (1) to lowering $P_N(s_i \rightarrow s_p)$ for any case in which the intended utterance s_i is not equal to the perceived utterance s_p ; this means that the conditional probability $P(s_i|s_p)$ will be higher when the perceived utterance was intended.

To decrease the noise rate, we doubled the length of time that the sentence preambles were shown to participants, from 1.5 seconds to 3 seconds. We also decreased the amount of time allotted for completing the sentences by a corresponding amount, so that the total amount of time allotted for the task remained the same as in previous experiments (14.5 seconds). This was done in order to ensure that any observed decrease in the rate of agreement errors was not caused by a change in the difficulty of the task.

Methods

Participants. We recruited 88 participants from Amazon's Mechanical Turk. Participants were restricted to those with IP addresses located in the US. Two participants did not provide responses for all critical trials but data from any trials they completed was included.

Procedure. Participants were presented with each sentence preamble for 3 seconds, and were given 11.5 seconds to retype and complete the preambles.

Materials. The experiment used the same materials and design as Experiment 1a.

Results

Agreement Errors. Our first goal was to assess whether the modifications to the task changed its overall difficulty for participants. The rate of miscellaneous errors (9%) was slightly higher than in Experiment 1a, suggesting that the task difficulty was unchanged or possibly greater than before. Thus, any observed decrease in the rate of agreement errors is not attributable to an overall decrease in the difficulty of the experiment.

The noisy-channel framework predicts a main effect of the task design: agreement error rates should be lower with increased presentation time. Because the rate of

agreement errors in the plural-head conditions in Experiment 1a was near the floor, we restricted the analysis to singular-plural condition, where most of the agreement errors occur (full analyses, which reveal the same effects, are presented in the supplementary materials). Empirical logit regressions show that there is a main effect of presentation time (by-subjects: $\beta=-0.41$, $SE=0.15$, $t=-2.73$, $p<0.01$; by-items: $\beta=-0.54$, $SE=0.19$, $t=-2.85$, $p<0.01$), so that the rate of agreement errors is lower when the presentation time is lengthened (Figure 1b).

Repetition Errors. Repetition errors occurred in 5.3% of the responses in the singular-plural condition, twice as often as any of the other conditions (Figure 2b), and numerically less than in Experiment 1a. However, presentation time did not significantly impact this rate (by-subjects: $\beta=-0.08$, $SE=0.13$, $t=-0.59$, $p=0.56$; by-items: $\beta=-0.16$, $SE=0.21$, $t=-0.78$, $p=0.44$).

Discussion

The finding that participants make fewer agreement errors when presentation time is extended (despite the task not being “easier” per se) is consistent with a prediction of the noisy-channel approach: that decreasing the noise rate should decrease the probability of inferring an incorrect number marking, and hence decrease the agreement error rate. Because previous accounts of agreement errors assume a veridical representation of the preamble, they do not provide an explanation of why adjusting the noise rate in this manner should affect the rate of agreement errors.

Experiment 1c

Experiment 1c aimed to test whether increasing the base rate of singular head nouns in the input would decrease the rate of agreement errors. If a lower proportion of the input preambles have a plural head, then comprehenders should be less likely to mistakenly infer that a plural head was intended. Using the terminology of Equation (1), increasing the prior probability $P_L(s_i)$ that the intended sentence s_i has a singular head will increase the conditional probability $P(s_i|s_p)$ that a singular head was intended. As a result, fewer agreement errors should be produced.

The rate of singular heads was increased by removing plural heads from the experimental items, so that all preambles containing a prepositional phrase contained a singular head. By keeping track of the statistics in their input, participants should therefore be able to learn that any preamble containing a prepositional phrase is singular.

Methods

Participants. 96 participants from Amazon’s Mechanical Turk were recruited. Seventeen participants did not provide responses for all critical trials but data from any trials they completed was included.

Procedure. This experiment used the same procedure as Experiment 1a and 1b.

Materials. The experiment used the items from Experiment 1a and 1b, restricted to the singular-singular and singular-plural conditions. The materials were presented in a Latin-square design. The fillers from Experiment 1a-b (of the form *The Noun*, e.g. *The boys*) were modified so that 40 contained plural nouns and 8 contained singular nouns. Thus, participants encountered the same number of plural and singular head nouns during the course of the experiment; as a consequence, participants could not determine whether to use a singular or plural verb prior to viewing the preamble.

Results

Agreement Errors. We evaluated whether decreasing the base rate of plurals decreases the rate of agreement errors. To do this, the error rate in Experiment 1c was compared to the error rate in Experiment 1a (Figure 1). The analysis was restricted to the singular-plural condition, as the plural-head conditions were absent from Experiment 1c, and the baseline error rate in the singular-singular condition was very low (1%) (full analyses are presented in the supplementary materials). Empirical logit regressions show that there was a significant effect of the base rate of plurals (by-subjects: $\beta=-0.61$, $SE=0.17$, $t=-3.57$, $p<0.001$; by-items: $\beta=-0.75$, $SE=0.17$, $t=-4.36$, $p<0.001$).

Repetition Errors. Repetition errors occurred in 2.3% of the responses in the singular-plural condition and 0.23% in the singular-singular condition (Figure 2). The base rate of singular heads had a significant effect on repetition errors (by-subjects: $\beta=-0.78$, $SE=0.12$, $t=-6.44$, $p<0.001$; by-items: $\beta=-0.82$, $SE=0.22$, $t=-3.66$, $p<0.001$), such that participants made fewer repetition errors when the base rate of singular heads was higher.

Discussion

These results demonstrate that increasing the base rate of singular head nouns in prepositional-phrase constructions decreases the rate of agreement errors. This is consistent with participants learning that singular PP constructions are more likely than plural PP constructions, and as a result being less likely to infer that a plural was intended. Importantly, these results suggest that participants were tracking the frequencies of whole constructions (e.g., the frequency of singular-plural constructions), and not just the frequency of singular or plural nouns, as an equal number of singular and

plural nouns appeared during the experiment. Memory-retrieval accounts generally assume that agreement errors occur due to false matches between memory retrieval cues and individual phrasal elements; it is not clear how the cue-matching process could be sensitive to the frequency of whole constructions. Feature-percolation accounts generally assume that agreement errors arise due to attraction effects between the different elements of a phrase; it is similarly not clear how the whole-construction frequency statistics could influence the strength of attraction in a manner necessary to explain the observed pattern (cf. Haskell, Thornton, & MacDonald, 2010).

Experiment 2

In Experiments 2 and 3, we tested a further prediction of the noisy-channel framework: that adding cues to the singular marking of the head noun should decrease the rate of agreement errors by reducing the noise likelihood, $P_N(s_i \rightarrow s_p)$. We tested this prediction in Experiment 2 by manipulating whether the determiner in the sentence preamble was definite (e.g., *The key to the cabinets*), as in Experiment 1a-c, or indefinite (e.g., *A key to the cabinets*) (see Hartsuiker et al. (2003) for a related experiment in Dutch and Eberhard (1997) for related work with quantifiers). In contrast to the English definite determiner *the*, the indefinite determiner *a* constrains the head noun to be singular, and therefore provides additional information about the intent of the speaker; if the comprehender encounters both an indefinite article and a singular plural marking, then it is unlikely that both of these cues were produced accidentally. In Equation (i), adding the indefinite cue to the perceived preamble s_p corresponds to decreasing the probability $P_N(s_i \rightarrow s_p)$ that a plural-headed preamble s_i would accidentally produce this preamble;

this, in turn, decreases the conditional probability $P(s_i|s_p)$ that a plural-headed preamble was intended. We therefore predict a lower rate of agreement errors when the determiner is an indefinite article.

Methods

Participants We recruited 112 participants from Amazon’s Mechanical Turk. Fifteen participants did not provide responses for all critical trials but data from any trials they completed was included.

Procedure The procedure used was the same as Experiment 1.

Materials We used nearly identical items as Experiment 1, with four conditions in a 2x2 design: two types of head noun (singular-definite, singular-indefinite) crossed with two types of second noun (singular-definite, plural-definite). In addition, we included two sets of fillers with plural head nouns: one with a singular noun in the prepositional phrase and another with a plural noun in the prepositional phrase. We included these materials so that the relative frequencies of singular and plural heads would be matched between experiments. The items were displayed in a Latin-square design, such that the frequency of plural and singular head nouns was balanced in the presentation. In addition, the 48 filler items from Experiment 1 were included, with 16 (one-third) of these fillers modified so that they began with an indefinite determiner.

Results

The noisy-channel framework predicts that the indefinite article should make the singular head items less confusable, and that this should decrease the rate of agreement errors. Because the baseline rate of agreement errors is very low in the singular-singular condition (1%), we do not expect to observe an effect of the indefinite article in this

condition. The present analyses are therefore restricted to the singular-plural condition (the full set of analyses reveal the same effects, and are presented in the supplementary materials). By-subjects and by-items empirical logit regressions found a significant effect of the determiner (by-subjects: $\beta=-0.30$, $SE=0.11$, $t=-2.61$, $p<0.01$; by-items: $\beta=-0.60$, $SE=0.20$, $t=-2.99$, $p<0.005$), so that agreement errors occur less frequently with the indefinite article.

Figure 3: Experiment 2: Proportion of agreement errors by preamble and article condition. Error bars represent standard error of the mean.

Discussion

The significant determiner effect provides evidence that adding a second cue to the singular marking of the head noun, in the form of an indefinite article, decreases the rate of agreement errors, consistent with the noisy-channel account's prediction that these cues would make the preamble less confusable with its alternatives. This effect of indefinite articles can be understood within the feature percolation account by assuming interactivity between syntactic and morphophonological levels of the production system (Hartsuiker et al., 2003). Similarly, on a Marking and Morphing account, quantifiers can provide singular marking to a previously unmarked singular head noun (Eberhard, 1997). It may also be possible to predict this effect from memory-retrieval models by positing that the indefinite article is used as a cue to aid in retrieval. However, this effect is predicted by the noisy-channel account without requiring the addition of any further stipulations.

Experiment 3

In Experiment 3, we again tested the prediction of the noisy-channel framework that adding cues to the singular marking of the head noun should decrease the rate of agreement errors by reducing the noise likelihood, $P_N(s_i \rightarrow s_p)$. We constructed sentence preambles consisting of a noun phrase modified by a relative clause, e.g. *The professor that is teaching the classes*. In this example, the preamble contains a full relative clause whose singular verb (the verb *is*) further constrains the head noun to be singular. We contrasted full relative clauses with reduced relative clauses, in which the expression *that is* was removed, e.g. *The professor teaching the classes*. In such reduced relative clauses, there is no additional constraint on the head noun's agreement marking. The noisy-

channel framework therefore predicts a higher rate of agreement errors for reduced relative clauses in contrast to full relative clauses. (See Bock & Miller (1991) for an experiment that used relative clauses with ambiguous number marking, e.g. *The professor that taught the classes.*)

Methods

Participants. We recruited 123 participants from Amazon’s Mechanical Turk. Twenty-three participants did not provide responses for all critical trials but data from any trials they completed was included.

Procedure. We used the same procedure from the previous experiments.

Materials. We constructed 32 sentence preambles consisting of a noun phrase modified by a relative clause. The head noun was always singular and the number marking of the local noun (singular, plural) was crossed with the form of the relative clause (full, reduced), creating 4 conditions. The items were presented in a Latin-square design. In addition, in order to keep the ratio of plural and singular head items matched between experiments – similar to the design of Experiment 2 – four additional filler conditions were included, with plural head nouns (crossing the number marking of the local noun (singular, plural) and the form of the relative clause (full, reduced)). The 48 filler items from the previous experiments were also included.

Results

As predicted by the noisy-channel framework, participants made fewer agreement errors in the full relative clause condition (see Figure 4). As in Experiment 2, the baseline rate of agreement errors in the singular-singular condition is low (2%), and therefore we do not expect to observe an effect of the relative clause in this condition.

The analyses presented here are restricted to the singular-plural condition (the full analyses, which reveal the same effects, are presented in the supplemental materials). Empirical logit regressions show an effect of the relative clause (by-subjects: $\beta=0.42$, $SE=0.10$, $t=4.06$, $p<0.001$; by-items: $\beta=0.69$, $SE=0.19$, $t=3.69$, $p<0.001$), so that agreement errors occur less often in the full relative condition.

Figure 4. Experiment 3: Proportion of agreement errors by preamble and relative clause condition

Discussion

The reduction of agreement errors in the full relative clause condition provides further evidence that additional cues to the singular marking of the head noun aid in the computation of number agreement. This effect of the full relative clause is consistent with a hierarchical feature percolation account because the intervening singular verb constitutes an additional singular feature source. Similarly, it may be possible to predict this effect from memory-retrieval models by positing that the singular verb is used as a cue to aid in retrieval. However, as with Experiment 2, this effect is predicted by the noisy-channel account without requiring the addition of any further stipulations.

General Discussion

In a series of experiments we showed that the noisy channel framework provides a straightforward account of patterns of agreement error in a sentence fragment continuation paradigm. In addition to validating the current version of the experimental paradigm, Experiment 1a showed that repetition errors on the head noun have the same distribution as agreement errors. These errors are predicted precisely if people are misperceiving the head noun. In Experiment 1b, it was shown that decreasing the perceived noise rate decreases agreement errors, though not repetition errors. If comprehenders expect to perceive the preamble accurately, then they will be less likely to infer that a different preamble was intended⁵. Experiment 1c showed that increasing the

⁵ An important consequence of the demonstration that changes to the noise significantly affects production of errors in the paradigm – reducing errors to close to baseline in our simple manipulation – is that the particular parameters of the paradigm for eliciting errors in these experiments are very important. This observation seems to be implicit in the design of the experiments in the existing literature – such that researchers have to titrate the method “just right” in order to observe significant numbers of errors for analysis – but this need for titration is unexplained in previous proposals. The rational inference approach offers a simple explanation of the large differences in results across seemingly slight differences in presentation parameters.

base rate of singular head nouns decreases the rate of agreement errors and repetition errors. Comprehenders are only likely to infer that their perceptual input is mistaken when there is a reasonably likely alternative; if only singular head nouns are observed in the input, then they will be unlikely to infer that a plural head noun was intended.

Experiments 2 and 3 provided evidence that additional cues to the singular marking of the head noun decreased the rate of agreement errors. These additional cues were unlikely to have been produced accidentally, making it more likely that the perceived sentence preamble was actually intended by the speaker.

Taken together, these experiments provide evidence that comprehenders entertain and adopt syntactic re-analyses of their language input to account for the possibility of noise. Consistent with Bergen, Levy, & Gibson (2012), we found evidence that these re-analyses are driven by the rational integration of syntactic expectations and expectations about the noise process. Along with other recent work, these results point to the value in viewing myriad sentence-processing phenomena as the consequence of rational, noisy-channel, probabilistic inference.

These experiments also argue for a novel interpretation of agreement elicitation errors, as being in part driven by rational inference during sentence comprehension. This framework can parsimoniously account for many phenomena across syntactic agreement and language processing more generally—though its full scope has yet to be fully explored. This is in contrast to traditional accounts of syntactic agreement errors, which rely on specific assumptions about sentence production (e.g., Eberhard et al., 2005) or memory-retrieval mechanisms (Wagers et al., 2009) in order to explain them. Further, a noisy-channel account is compatible with learning-based views of agreement errors (e.g.,

Haskell, Thornton, & MacDonald, 2010), which suggest that the asymmetry falls out of the nature of co-occurrences to which comprehenders are exposed in everyday language use. Singular-plural noun phrases followed by a plural verb are more frequent than plural-singular noun phrases due to the commonplace use of collectives (e.g., *A majority of people-oriented companies are likely to adopt them*). The argument for a role for distributional learning is consistent with a rational decoding perspective on language comprehension because the frequency of co-occurrence of words or constructions can be straightforwardly understood as contributing to the prior.

It is important to note that we have not addressed the full breadth of syntactic agreement phenomena that are discussed in this rich literature. While some results that are not directly examined here are straightforwardly predicted by this view—for instance, that languages with higher pro-drop rates (i.e., a higher noise rate) have higher rates of agreement errors (Bock & Foote, 2012)—the noisy-channel model, in the simple form laid out here, is unlikely to account for all the known patterns. For instance, this account does not predict the difference between subject-verb agreement and reflexive agreement reported in Dillon, Mishler, Sloggett, & Phillips (2013). However, it may be that a reflexive agreement intrusion effect would manifest itself in a production setting. Future work is necessary to more conclusively determine whether cases like anaphora violate noisy channel predictions. Similarly, to what extent the noisy channel framework can accommodate semantic integration (Solomon & Pearlmutter, 2004; Gillespie & Pearlmutter, 2011; 2013) and conceptual number effects (Eberhard, 1999; Vigliocco, Butterworth & Semenza, 1995; Brehm & Bock, 2013; 2016) on agreement attraction is an open question.

Further, in this work we focus on the agreement error elicitation method, the outcomes of which reflect both comprehension and production processes. Agreement errors stemming from *pure* production processes certainly exist as well and may be governed by a unique set of constraints, separable from comprehension. A full discussion of production-side pressures on syntactic agreement is beyond the scope of this paper (though see Ferreira & Bock, 2014 for a recent overview). However, it is critical for the production literature to consider the comprehension-side pressures, such as noise, involved in widely used experimental paradigms as this has important implications for what can be concluded about agreement errors and for language production models more broadly.

References

- Aylett, M., & Turk, A. (2004). The smooth signal redundancy hypothesis: A functional explanation for relationships between redundancy, prosodic prominence and duration in spontaneous speech. *Language and Speech*, 47, 31–56.
- Badecker, W., Kuminiak, F. (2007). Morphology, agreement and working memory retrieval in sentence production: Evidence from gender and case in Slovak. *Journal of Memory and Language*, 56, 65–85.
- Barr, D. J. (2008). Analyzing ‘visual world’ eyetracking data using multilevel logistic regression. *Journal of Memory and Language*, 59, 457–474.
- Bock, J. K., & Ferreira, V. (2014). Syntactically speaking. In M. Goldrick, V. Ferreira, & M. Miozzo (Eds.), *The oxford handbook of language production* (pp. 21–46). Oxford: Oxford University Press
- Bock, K., & Miller, C. A. (1991). Broken agreement. *Cognitive Psychology*, 23, 45–93.
- Dell, G. S., & Reich, P. A. (1981). Stages in sentence production: An analysis of speech error data. *Journal of verbal learning and verbal behavior*, 20(6), 611–629.
- Dillon, B., Mishler, A., Sloggett, S., & Phillips, C. (2013). Contrasting intrusion profiles for agreement and anaphora: Experimental and modeling evidence. *Journal of Memory and Language*, 69, 85–103.
- Eberhard, K. M. (1997). The Marked Effect of Number on Subject–Verb Agreement. *Journal of Memory and Language*, 36(36), 147–164.
- Eberhard, K. M. (1999). The accessibility of conceptual number to the processes of subject–verb agreement in English. *Journal of Memory and Language*, 41, 560–578.

- Eberhard, K.M., Cutting, J. C., & Bock, K. (2005). Making syntax of sense: Number agreement in sentence production. *Psychological Review*, 112. 531–559.
- Franck, J., Vigliocco, G., Nicol, J. (2002). Subject-verb agreement errors in French and English: The role of syntactic hierarchy. *Language and Cognitive Processes*, 17. 371–404.
- Frazier, L., & Rayner, K. (1987). Resolution of syntactic category ambiguities: Eye movements in parsing lexically ambiguous sentences. *Journal of Memory and Language*, 26, 505–526.
- Gibson, E., Bergen, L., & Piantadosi, S. T. (2013). Rational integration of noisy evidence and prior semantic expectations in sentence interpretation. *Proceedings of the National Academy of Sciences*, 110. 8051-8056.
- Gibson, E. & Fedorenko, E. (2012). The need for quantitative methods in syntax and semantics research. *Language and Cognitive Processes*, 28. 88-124.
- Gillespie, M., & Pearlmutter, N. J. (2013). Against structural constraints in subject–verb agreement production. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39, 515-528.
- Hartsuiker, R. J., Antón-Méndez, I., van Zee, M. (2001). Object attraction in subject-verb agreement construction. *Journal of Memory and Language*, 45. 546–572.
- Hartsuiker, R. J., Schriefers, H. J., Bock, K., & Kikstra, G. M. (2003). Morphophonological influences on the construction of subject-verb agreement. *Memory & Cognition*, 31. 1316-1326.
- Levy R (2008). A noisy-channel model of rational human sentence comprehension under uncertain input. In Proceedings of the 13th Conference on Empirical Methods in

Natural Language Processing, pp. 234–243.

Levy, R., Bicknell, K., Slattery, T., & Rayner, K. (2009). Eye movement evidence that readers maintain and act on uncertainty about past linguistic input. *Proceedings of the National Academy of Sciences*, 106. 21086-21090.

Levy, R. (2011). Integrating surprisal and uncertain-input models in online sentence comprehension: formal techniques and empirical results. In *Proceedings of the 49th Annual Meeting of the Association for Computational Linguistics: Human Language Technologies-Volume 1* (pp. 1055-1065). Association for Computational Linguistics.

MacDonald, M. (1993). The interaction of lexical and syntactic ambiguity. *Journal of Memory and Language*, 32, 692–692.

MacKay, D. J. C. (2003). *Information Theory, Inference and Learning Algorithms* (Cambridge University Press, Cambridge).

Marslen-Wilson, W. (1975). Sentence perception as an interactive parallel process. *Science*, 189. 226.

Samuel, A. G. (1981). Phonemic restoration: Insights from a new methodology. *Journal of Experimental Psychology: General*, 110(4), 474–494.

<http://doi.org/10.1037//0096-3445.110.4.474>

Shannon, C. (1948). A mathematical theory of communication. *Bell System Technical Journal*, 27. 623–656.

Slattery, T. (2009). Word misperception, the neighbor frequency effect, and the role of sentence context: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, 35. 1969-1975

- Solomon, E. S. & Pearlmutter, N. J. (2004). Semantic integration and syntactic planning in language production. *Cognitive Psychology*, 49, 1–46.
- Stemberger, J. P. (1985). Bound morpheme loss errors in normal and agrammatic speech: One mechanism or two? *Brain and Language*, 25(2), 246–256.
- Vigliocco, G., Butterworth, B., & Semenza, C. (1995). Constructing subject-verb agreement in speech: The role of semantic and morphological factors. *Journal of Memory and Language*, 34, 186–215
- Vigliocco, G. & Nicol, J. (1998). Separating hierarchical relations and word order in language production: Is proximity concord syntactic or linear? *Cognition*, 68, B13–B29.
- Xu, F. & Tenenbaum, J. B. (2007). Word learning as Bayesian inference. *Psychological Review*, 114, 245–272.

Acknowledgments

This work was supported by National Science Foundation Grants 0844472 and 1534318 from the Linguistics Program to E.G. We would also like to thank Evelina Fedorenko, Kyle Mahowald, Roger Levy, Melissa Kline, Richard Futrell, Steve Piantadosi, and Laurel Brehm for helpful comments and discussions.

Supplemental Material

By Participants	β	SE	t-value	p-value
(Intercept)	-1.848	0.046	-40.218	<.001
Head Noun Number	0.282	0.092	3.070	0.002
Local Noun Number	-0.465	0.092	-5.061	<.001
Head Noun Number x Local Noun Number	-0.922	0.184	-5.019	<.001
By Items	β	SE	t-value	p-value
(Intercept)	-2.313	0.071	-32.452	<.001
Head Noun Number	0.375	0.143	2.633	0.010
Local Noun Number	-0.599	0.143	-4.201	<.001
Head Noun Number x Local Noun Number	-1.317	0.285	-4.618	<.001

S1. Experiment 1a: Weighted Empirical Logit Regressions of Number of Errors from Head and Local Noun Number.

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-4.284	0.376	-11.392	<.001
Head Noun Number	0.598	0.374	1.599	0.11
Local Noun Number	-1.54	0.383	-4.019	<.001
Head Noun Number x Local Noun Number	-2.796	0.756	-3.7	<.001
Random Effects	SD			
(Intercept) Items	0.611			
(Intercept) Participants	1.291			
Observations: 1425, Participants: 78, Items: 32				

S2. Experiment 1a: Logistic Mixed-Effects Regression of Number of Errors from Head and Local Noun Number.

By Participants	β	SE	t-value	p-value
(Intercept)	-1.951	0.039	-50.494	<.001
Head Noun Number	-0.027	0.077	-0.349	0.727
Local Noun Number	-0.338	0.077	-4.369	<.001
Head Noun Number x Local Noun Number	-0.560	0.155	-3.625	<.001
By Items	β	SE	t-value	p-value
(Intercept)	-2.421	0.076	-32.028	<.001
Head Noun Number	-0.138	0.151	-0.911	0.364
Local Noun Number	-0.591	0.151	-3.908	<.001
Head Noun Number x Local Noun Number	-0.908	0.302	-3.004	0.003

S3. Experiment 1a: Weighted Empirical Logit Regressions of Number of Repetition Errors from Head and Local Noun Number.

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-4.79	0.49	-9.774	<.001
Head Noun Number	-0.903	0.572	-1.58	0.114
Local Noun Number	-1.729	0.573	-3.019	0.003
Head Noun Number x Local Noun Number	-2.98	1.147	-2.597	0.009
Random Effects	SD			
(Intercept) Items	1.103			
(Intercept) Participants	0.866			
Observations: 1400, Participants: 78, Items: 32				

S4. Experiment 1a: Logistic Mixed-Effects Regression of Number of Repetition Errors from Head and Local Noun Number.

By Participants	β	SE	t-value	p-value
(Intercept)	-1.450	0.076	-19.200	<.001
Presentation Time	-0.413	0.151	-2.733	0.007
By Items	β	SE	t-value	p-value
(Intercept)	-1.768	0.095	-18.591	<.001
Presentation Time	-0.542	0.190	-2.850	0.006

S5. Experiment 1b: Weighted Empirical Logit Regressions of Number of Agreement Errors from Presentation Time (in Singular-Plural condition).

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-3.339	0.387	-8.627	<.001
Presentation Time	-1.068	0.422	-2.53	0.011
Random Effects	SD			
(Intercept) Items	0.78			
(Intercept) Participants	1.561			
Observations: 762, Participants: 163, Items: 32				

S6. Experiment 1b: Logistic Mixed-Effects Regression of Number of Agreement Errors from Presentation Time (in Singular-Plural condition).

By Participants	β	SE	t-value	p-value
(Intercept)	- 1.918		- 62.089	<.001
Head Noun Number	0.135	0.062	2.184	0.029
Local Noun Number	- 0.437	0.062	-7.066	<.001
Presentation Time	- 0.141	0.062	-2.275	0.023
Head Noun Number x Local Noun Number	- 0.729	0.124	-5.902	<.001

Head Number x Local Number	- 0.294	0.124	-2.382	0.017
Head Number x Presentation Time	0.057	0.124	0.460	0.645
Local Number x Presentation Time	0.386	0.247	1.563	0.119
Head Number x Local Number x Presentation Time	- 1.918	0.031	- 62.089	<.001
By Items	β	SE	t-value	p-value
(Intercept)	- 2.436	0.047	- 51.400	<.001
Head Noun Number	0.097	0.095	1.023	0.307
Local Noun Number	- 0.652	0.095	-6.883	<.001
Presentation Time	- 0.245	0.095	-2.584	0.010
Head Noun Number x Local Noun Number	- 1.173	0.190	-6.186	<.001
Head Number x Local Number	- 0.557	0.190	-2.937	0.004
Head Number x Presentation Time	- 0.107	0.190	-0.564	0.573
Local Number x Presentation Time	0.288	0.379	0.761	0.447
Head Number x Local Number x Presentation Time	- 2.436	0.047	- 51.400	<.001

S7. Experiment 1b: Weighted Empirical Logit Regressions of Number of Agreement Errors from Head and Local Noun Number and Presentation Time.

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-6.276	9.253	-0.678	0.498
Head Noun Number	-3.772	18.501	-0.204	0.838
Local Noun Number	-5.319	18.501	-0.288	0.774
Presentation Time	-4.109	18.503	-0.222	0.824
Head Noun Number x Local Noun Number	-10.172	37.001	-0.275	0.783
Head Number x Local Number	-8.709	37.002	-0.235	0.814
Head Number x Presentation Time	-7.624	37.002	-0.206	0.837
Local Number x Presentation Time	-14.836	74.002	-0.2	0.841
Head Number x Local Number x Presentation Time	-6.276	9.253	-0.678	0.498
Random Effects	SD			
(Intercept) Items	0.476			
(Intercept) Participants	1.28			
Observations: 3135, Participants: 164, Items: 32				

S8. Experiment 1b: Logistic Mixed-Effects Regression of Number of Agreement Errors from Head and Local Noun Number and Presentation Time.

By Participants	β	SE	t-value	p-value
(Intercept)	-1.693	0.064	-26.478	<.001
Presentation Time	-0.076	0.128	-0.591	0.555
By Items	β	SE	t-value	p-value
(Intercept)	-2.050	0.105	-19.462	<.001
Presentation Time	-0.165	0.211	-0.781	0.438

S9. Experiment 1b: Weighted Empirical Logit Regressions of Number of Repetition Errors from Presentation Time (in Singular-Plural condition).

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-4.009	0.595	-6.734	<.001
Presentation Time	-0.145	0.465	-0.311	0.755
Random Effects	SD			
(Intercept) Items	0.983			
(Intercept) Participants	1.459			
Observations: 731, Participants: 162, Items: 32				

S10. Experiment 1b: Logistic Mixed-Effects Regression of Number of Repetition Errors from Presentation Time (in Singular-Plural condition).

By Participants	β	SE	t-value	p-value
(Intercept)	-1.547	0.085	-18.196	<.001
Base Rate of Plurals	-0.607	0.170	-3.567	<.001
By Items	β	SE	t-value	p-value
(Intercept)	-1.872	0.086	-21.753	<.001
Base Rate of Plurals	-0.750	0.172	-4.357	<.001

S11. Experiment 1c: Weighted Empirical Logit Regressions of Number of Agreement Errors from Base Rate of Plurals (in Singular-Plural condition).

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-3.424	0.344	-9.967	<.001
Base Rate of Plurals	-1.097	0.415	-2.643	0.008
Random Effects	SD			
(Intercept) Items	0.647			
(Intercept) Participants	1.733			
Observations: 1157, Participants: 157, Items: 32				

S12. Experiment 1c: Logistic Mixed-Effects Regression of Number of Agreement Errors from Base Rate of Plurals (in Singular-Plural condition).

By Participants	β	SE	t-value	p-value
(Intercept)	-2.067	0.051	-40.140	<.001
Local Noun Number	-1.040	0.103	-10.101	<.001
Base Rate of Plurals	-0.721	0.103	-6.996	<.001
Local Noun Number x Base Rate of Plurals	-0.228	0.206	-1.107	0.269

By Items	β	SE	t-value	p-value
(Intercept)	-2.566	0.068	-37.827	<.001
Local Noun Number	-1.388	0.136	-10.234	<.001
Base Rate of Plurals	-0.881	0.136	-6.493	<.001
Local Noun Number x Base Rate of Plurals	-0.262	0.271	-0.967	0.336

S13. Experiment 1c: Weighted Empirical Logit Regressions of Number of Agreement Errors from Local Noun Number and Base Rate of Plurals.

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-4.948	0.392	-12.618	<.001
Local Noun Number	-3.375	0.472	-7.153	<.001
Base Rate of Plurals	-1.424	0.559	-2.546	0.011
Local Noun Number x Base Rate of Plurals	-0.686	0.924	-0.743	0.457
Random Effects	SD			
(Intercept) Items	0.518			
(Intercept) Participants	1.609			
Observations: 2352, Participants: 157, Items: 32				

S14. Experiment 1c: Logistic Mixed-Effects Regression of Number of Agreement Errors from Local Noun Number and Base Rate of Plurals.

By Participants	β	SE	t-value	p-value
(Intercept)	-2.046	0.061	-33.753	<.001
Base Rate of Plurals	-0.781	0.121	-6.442	<.001
By Items	β	SE	t-value	p-value
(Intercept)	-2.376	0.112	-21.280	<.001
Base Rate of Plurals	-0.816	0.223	-3.656	0.001

S15. Experiment 1c: Weighted Empirical Logit Regressions of Number of Repetition Errors from Base Rate of Plurals (in Singular-Plural condition).

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-5.08	0.862	-5.892	<.001
Base Rate of Plurals	-1.084	0.521	-2.078	0.038
Random Effects	SD			
(Intercept) Items	1.442			
(Intercept) Participants	1.64			
Observations: 1097, Participants: 156, Items: 32				

S16. Experiment 1c: Logistic Mixed-Effects Regression of Number of Repetition Errors from Base Rate of Plurals (in Singular-Plural condition).

By Participants	β	SE	t-value	p-value
(Intercept)	-1.325	0.057	-23.209	<.001
Determiner Type	-0.298	0.114	-2.606	0.010

By Items	β	SE	t-value	p-value
(Intercept)	-1.799	0.101	-17.876	<.001
Determiner Type	-0.601	0.201	-2.986	0.004

S17. Experiment 2: Weighted Empirical Logit Regressions of Number of Agreement Errors from Determiner Type (in Singular-Plural condition).

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-8.708	1.58	-5.512	<.001
Determiner Type	-3.367	1.106	-3.045	0.002
Random Effects	SD			
(Intercept) Participants	6.618			
Observations: 356, Participants: 97, Items: 32				

S18. Experiment 2: Logistic Mixed-Effects Regression of Number of Agreement Errors from Determiner Type (in Singular-Plural condition). Model with random intercepts for items did not converge.

By Participants	β	SE	t-value	p-value
(Intercept)	-1.459	0.033	-44.081	<.001
Local Noun Number	-0.125	0.066	-1.882	0.061
Determiner Type	-0.268	0.066	-4.045	<.001
Local Noun Number x Determiner Type	0.346	0.132	2.613	0.009
By Items	β	SE	t-value	p-value
(Intercept)	-2.076	0.063	-33.198	<.001
Local Noun Number	-0.246	0.125	-1.968	0.051
Determiner Type	-0.554	0.125	-4.433	<.001
Local Noun Number x Determiner Type	0.710	0.250	2.836	0.005

S19. Experiment 2: Weighted Empirical Logit Regressions of Number of Agreement Errors from Local Noun Number and Determiner Type.

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-6.699	2.127	-3.15	0.002
Local Noun Number	-1.735	0.764	-2.273	0.023
Determiner Type	-2.11	0.762	-2.769	0.006
Local Noun Number x Determiner Type	1.124	1.439	0.782	0.435
Random Effects	SD			
(Intercept) Participants	3.166			
Observations: 749, Participants: 102				

S20. Experiment 2: Logistic Mixed-Effects Regression of Number of Agreement Errors from Local Noun Number and Determiner Type. Model with random intercepts for items did not converge.

By Participants	β	SE	t-value	p-value
(Intercept)	-1.442	0.051	-28.224	<.001

Relative Clause Type	0.415	0.102	4.058	<.001
By Items	β	SE	t-value	p-value
(Intercept)	-1.972	0.093	-21.187	<.001
Relative Clause Type	0.686	0.186	3.687	<.001

S21. Experiment 3: Weighted Empirical Logit Regressions of Number of Agreement Errors from Relative Clause Type (in Singular-Plural condition).

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-3.838	0.716	-5.357	<.001
Relative Clause Type	1.584	0.594	2.666	0.008
Random Effects	SD			
(Intercept) Participants	1.051			
(Intercept) Items	0.664			
Observations: 409, Participants: 100, Items: 32				

S22. Experiment 3: Logistic Mixed-Effects Regression of Number of Agreement Errors from Relative Clause Type (in Singular-Plural condition).

By Participants	β	SE	t-value	p-value
(Intercept)	-1.552	0.032	-48.815	<.001
Local Noun Number	0.338	0.064	5.321	<.001
Relative Clause Type	-0.219	0.064	-3.449	0.001
Local Noun Number x Relative Clause Type	-0.153	0.127	-1.202	0.230
By Items	β	SE	t-value	p-value
(Intercept)	-2.204	0.055	-39.935	<.001
Local Noun Number	0.521	0.110	4.723	<.001
Relative Clause Type	-0.464	0.110	-4.200	<.001
Local Noun Number x Relative Clause Type	-0.330	0.221	-1.496	0.137

S23. Experiment 3: Weighted Empirical Logit Regressions of Number of Agreement Errors from Local Noun Number and Relative Clause Type.

Fixed Effects	β	SE	z-value	p-value
(Intercept)	-5.194	0.76	-6.836	<.001
Local Noun Number	1.775	0.659	2.691	0.007
Relative Clause Type	-1.588	0.662	-2.399	0.016
Local Noun Number x Relative Clause Type	-0.01	1.292	-0.008	0.994
Random Effects	SD			
(Intercept) Items	0.825			
(Intercept) Participants	1.508			
Observations: 845, Participants: 108, Items: 32				

S24. Experiment 3: Logistic Mixed-Effects Regression of Number of Agreement Errors from Local Noun Number and Relative Clause Type.