The Bolts and Nuts of Language Processing:
An Investigation into the Noisy-channel Processing of Binomials

By

ZACHARY NICHOLAS HOUGHTON
THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF ARTS

in

Psychology

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

———————————————————
Fernanda Ferreira, Chair

———————————————————
Emily Morgan

———————————————————
John Henderson

Committee in Charge

2025

Table of contents

Abstract

There is often more than one way to convey the same meaning. For example, one might go to the store to buy a *radio and television*, or one might just as easily go to the store to buy a *television and radio*. Recent studies have shown that for high-frequency binomials, speakers develop a strong preference for one binomial ordering (e.g., *bread and butter*) over the alternative (e.g., *butter and bread*). This polarization of preferences for high-frequency items is called frequency-dependent preference extremity. How does this preference emerge over time? One possibility is that it is a consequence of noisy-channel processing. That is, for high-frequency items, it is possible that when a listener hears *butter and bread*, they assume that the speaker actually intended to say *bread and butter*. In order to test this, we examined whether hearing *butter and bread* actually primes *bread and butter* more than it does *butter and bread*. However, we find that both the frequent and infrequent orderings of binomials prime the exact ordering they were heard in, suggesting that noisy-channel processing may not be the processing mechanism behind frequency-dependent preference extremity.

1. Introduction

Humans have a great deal of flexibility when it comes to linearizing our abstract thoughts into discrete words or phrases. For example, to express uncertainty, we have a variety of options ranging from familiar expressions such as *I don't know*, to more novel expressions, such as *to me, it is unknown*. In other words, when speaking we are faced with the decision of either accessing a holistically stored expression or generating a novel expression by combining words using knowledge of the grammar.

Traditionally, the assumption with respect to this trade off between item-specific and generative knowledge was that it is a function of a word or phrase's semantic compositionality (i.e., the degree to which the phrase's meaning could be derived from the individual words or morphemes that comprise it; Chomsky, 1965; Pinker & Ullman, 2002). For example, according to generativist theories, regular multi-morphemic words can be composed using rules of the language. As such, the word *cats* would be generated by accessing the holistically stored word, *cat*, and then generating *cats* by using knowledge of the grammar. Similarly, multi-word phrases, such as *I don't know* would be generated by accessing each of the individual words in the phrase, *I*, *don't*, and *know*, and then combining them.

Additionally, some formal syntacticians have also argued that even in cases where a multi-word phrase (e.g., an idiom) is stored holistically, the phrase is still licensed by the grammar (e.g., Culicover et al., 2017). For example, Culicover et al. (2017) demonstrated that multi-word phrases often following the rules of the grammar. They argued that since the verb in the phrase *kicked the bucket* can still be inflected as in *she may kick the bucket soon*, that even in cases where a multi-word phrase is stored holistically, it is stored with its phrase structure rules.

Generativist theories gained a great deal of traction, partially due to concerns about memory limitations. However, more recently we have learned that the brain has a much larger memory capacity than we once thought. For example, Wang et al. (2003) demonstrated that the human brain can store an upwards of 10^{8432} bits. Further, Mollica & Piantadosi (2019) estimated that the upper bound of memory that it would require to store linguistic knowledge is ten million

bits of information, which is well within the estimated amount of storage that the human brain has.

As knowledge of the memory capacity of the brain increased, alternative accounts of storage began gaining traction. These theories grew largely out of the phonetics literature where generativists' approach to language fell short. For example, Bybee (2002) demonstrated that the phonetic reduction of a sound advances more quickly in high-frequency words than low-frequency words. If words are a combination of abstract phonemes, then the reduction of a phoneme should proliferate across every word that contains the phoneme. In other words, it's hard to account for the context-specificity of phoneme realizations without a storage mechanism that contains context-specific phonetic detail.

Similarly, there is evidence that phonetic representations may be stored holistically (i.e., as exemplars instead of abstract phoneme representations). For example, in their seminal paper Mc-Murray et al. (2008) demonstrated that people are sensitive to gradient changes of within-category voice onset timing (VOT). VOT is a measure of when the vocal chords begin flapping with respect to the production of a phoneme. While VOT is a continuous measure, it is used by English listeners to make a binary decision as to whether a sound is voiced or voiceless. Following this, if phonemes are represented as abstract categories (e.g., just *p* or *b*), then VOT should only influence listener's perception if the change in VOT results in a change in the phoneme. If two sounds vary in VOT but are still classified as *p*, participants should not be sensitive to the difference in VOT (if they're decomposing the word into abstract phonemes).

McMurray et al. (2008) demonstrated that listeners *are* sensitive to within-category VOT. Specifically, they presented participants with words such as *barricade/parakeet*, where the initial sounds were either voiced or voiceless stops. They then systematically manipulated the VOT for the initial stop and measured the proportion of participants' fixations to the competitor. They found that within-category variability of VOT affected the proportion of fixations to the competitor, suggesting sensitivity to within-category variability in VOT. It is difficult to account for this sensitivity if words are composed via abstract representations of sounds (i.e., phonemes). While it may be possible to account for the results in McMurray et al. (2008) without storing exemplars

(e.g., by using the phonetic detail to facilitate the judgement of whether a sound is /p/ or /b/ but none-the-less still implementing a categorical judgement), the phonetic information must be stored somewhere (because participants must have some knowledge of the distribution of VOTs for a /p/ or a /b/). As such, this finding has been taken as evidence that people are storing exemplars of sounds when they experience them as opposed to only storing abstract representations. While this is a phenomenon at the individual sound-level, the connection to multi-word storage may be clear by now: if people are storing individual sounds instead of simply storing phoneme-level abstractions, then the same may be true on the multi-word phrase level: people may store phrases holistically instead of generating them through abstract representations of the individual words.

The evidence for item-specific representations of sounds naturally sparked similar theoretical debates about the representations of multi-word phrases. For example, Bybee & Scheibman (1999) examined the phonetic reduction of *don't* in various contexts. They found that *don't* is more greatly reduced in *I don't know* than in lower-frequency phrases such as *I don't go*. In other words, the phonetic reduction of *I don't know* cannot be attributed to the phonetic reduction of any of the individual parts in isolation. This suggests that *I don't know* has a representation separate from the individual parts.[1] Bybee & Scheibman (1999) showed similar results for other high-frequency phrases as well, such as *have to*, *want to*, etc. Similarly, Yi (2002) demonstrated that tensification in certain multi-word phrases in Korean is also context-specific. Specifically, in Korean certain consonants become tense when they occur after the future tense marker. Yi (2002) demonstrated that this tensification is more frequent in high-frequency phrases. The context-specificity of the phonetic reduction of multi-word phrases is strong evidence for the holistic storage of multi-word phrases.

In the Psycholinguistics literature, there has been a rich literature examining the multi-word holistic storage of binomials (Houghton & Morgan, 2023, 2024; Morgan et al., 2023; Morgan & Levy, 2015, 2016a, 2016b, 2024; Siyanova-Chanturia et al., 2011). For example, Siyanova-

---

[1] One could account for this by positing adjacency effects such as co-articulation, which definitely are responsible to a certain extent for phonetic reduction. However, this seems unlikely to explain all of the effects seen in Bybee & Scheibman (1999) since even in the phrase *I don't know, don't* seems to only be reducible in specific contexts. For example, in sentences that contain an additional clause (e.g., in a sentence containing a complementizer phrase, such as *I don't know what you're talking about, I don't know* cannot be reduced as much as it can be when it's produced alone (e.g., as a response to a simple question) where it can be reduced to only a nasally vowel with intonation.

Chanturia et al. (2011) demonstrated that binomials are read faster in their frequent order (e.g., *bread and butter*) than in their infrequent ordering (e.g., *butter and bread*). At a first glance, if binomials are represented and processed word-by-word (i.e., if binomials are not holistically stored) then it may seem difficult to account for the results of Siyanova-Chanturia et al. (2011) since the individual words are identical across different orderings of the same binomial (i.e., the words in *cats and dogs* are the same as in *dogs and cats*).[2] However, one possible account for the asymmetrical ordering preferences is that humans learn abstract preferences for the ordering of words in phrases (e.g., a preference for short words first). Morgan & Levy (2016a) examined this possibility by creating a corpus of binomials and annotating them for semantic and phonological constraints known to influence binomial orderings (Benor & Levy, 2006). They then created a logistic model to combine these constraints into a single generative preference value that indicated the direction and magnitude of the preference.

Morgan & Levy (2016a) examined whether human ordering preferences are driven by these abstract preferences for binomials ranging from low to high overall frequency (where overall frequency is the total number of times a binomial occurs in either ordering, e.g., the number of times *bread and butter* occurs plus the number of times *butter and bread* occurs). Specifically, they used a self-paced reading task where participants read binomials in sentence contexts. They found that for low-frequency binomials, human reading times were driven primarily by generative preferences, however for high-frequency binomials human reading times were driven primarily by relative frequency (i.e., the proportion of counts in the alphabetical ordering to the nonalphabetical ordering). Their results suggest that humans compose low-frequency binomials using abstract knowledge of the language, however for high-frequency binomials humans store and access a holistic representation of the entire binomial.

---

[2]Although see Frazier et al. (2000) for an argument that posits coordinate structures as asymmetrical adjunction structures headed by the first conjunct, which may also account for the different ordering effects seen in Siyanova-Chanturia et al. (2011).

1.1. Frequency-dependent Preference Extremity

Holistic storage also makes rich predictions about language change that have been borne out in the literature. For example, there is evidence for a phenomenon called **frequency-dependent preference extremity**, wherein ordering preferences become more extreme for high-frequency items relative to low-frequency items (Liu & Morgan, 2020, 2021; Morgan & Levy, 2016a). A great deal of evidence for this phenomenon comes from the literature on binomial ordering preferences, where it has been demonstrated that humans develop strong ordering preferences for high-frequency binomials but not low-frequency binomials (Morgan & Levy, 2015; e.g., a strong preference for *bread and butter* over *butter and bread*, but not a strong preference for *radio and television* over *television and radio*; Morgan & Levy, 2016a, 2016b).

Evidence of frequency-dependent preference extremity is not limited to binomials either. Liu & Morgan (2020) demonstrated that the dative alternation (e.g., *give him the ball* vs *give the ball to him*) also shows evidence of frequency-dependent preference extremity. Specifically, they found that for high-frequency verbs, there is a stronger preference for using one dative alternation structure over the other than for low-frequency verbs. Similarly, Liu & Morgan (2021) examined the ordering of adjectives in adjective-adjective-noun (AAN) phrases (e.g., *dark blue sky*). They found that AAN phrases with higher overall frequency (where overall frequency is the sum of counts in either adjective ordering; e.g., count of *big blue sky* plus *blue big sky*.) show more polarized ordering preferences.

One way to account for frequency-dependent preference extremity is to posit that high-frequency binomials are stored holistically. For example, as mentioned earlier there is evidence that humans rely on abstract preferences for low-frequency binomials but rely on their experience with a binomial for high-frequency binomials. This might help to explain why people develop strong preferences for high-frequency binomials but not low-frequency binomials. However, while holistic storage may be a driving factor for frequency-dependent preference extremity, it isn't enough by itself to account for this phenomenon. That is, high-frequency binomials being stored holistically does not necessarily lead to them being used more.

In addition to holistic storage, it is possible that frequency-dependent preference ex-

tremity arises as an interaction between imperfect learning and transmission across generations (Houghton & Morgan, 2024; Morgan & Levy, 2016b). For example, Morgan & Levy (2016b) argued that humans have a bias to regularize[3] (i.e., a bias for one form to become preferred over competing alternatives) productions to decrease variability (Hudson Kam & Newport, 2005). It is possible that this regularization bias causes high-frequency binomials to become more polarized (i.e., more regularized). Indeed, they found that a computational model that contains a frequency-independent regularization bias does result in frequency-dependent preference extremity. They demonstrated that this is because in their model, learners rely on their prior knowledge (abstract preferences in this case) when there isn't enough data (such as in the case of lower frequency binomials), but when they have enough data they overcome their prior knowledge and produce more regularized/polarized productions.

Specifically Morgan & Levy (2016b) used a 2-alternative iterated learning paradigm (Reali & Griffiths, 2009) to simulate the evolution of binomial ordering preferences across generations of speakers. In their model, a learner first hears N binomial expressions. The learner's goal is to learn the underlying distribution that generated the binomials. For example, if a speaker produces *bread and butter* with 0.9 probability and *butter and bread* with 0.1 probability, the goal of the learner is to learn these probabilities. After learning these preferences, the learner then produces N binomial expressions for the next generation of learners. This continues iteratively for N generations of learners.

Typically, learners in a 2-alternative iterated learning paradigm are modeled as rational Bayesian learners using Bayes' rule. For example, in a classical 2-alternative iterated learning paradigm, the learner estimates the probability of the binomial being ordered alphabetically (alphabetical ordering is used as a relatively neutral reference order). The learner estimates this by multiplying the probability of observing the alphabetical ordering of a given binomial under a given hypothesis about the ordering preferences (the likelihood, $P(x_1|\theta_1)$, Equation 1) by the prior probability of that hypothesis ($P(\theta_1)$, Equation 2).

In other words, the likelihood is equivalent to the probability of a sequence of binomials

---

[3]Following Morgan & Levy (2016b), we define *regularization* as a reduction in variability/entropy of a distribution.

containing x_1 binomials in alphabetical ordering generated by a speaker that produces the alphabetical ordering with some probability θ_1. The prior is the probability distribution over the values of θ_1, which describe the learner's prior beliefs about the probability of each ordering. Equation 1 and Equation 2 provide the mathematical formalization of the likelihood and prior[4] respectively in the 2-alternative iterated learning paradigm (Reali & Griffiths, 2009).

$$P(x_1|\theta_1) = \binom{N}{x_1}\theta_1^{x_1}(1-\theta_1)^{N-x_1} \tag{1}$$

$$P(\theta_1) = Beta(\frac{\alpha}{2}, \frac{\alpha}{2}) \tag{2}$$

However, Morgan & Levy (2016b) demonstrated that this approach does not capture the effects of frequency-dependent preference extremity. As such, they modified the prior such that there was a regularization parameter. Specifically, they used the regularized incomplete beta function, which includes a regularization parameter. This parameter is set to the same value for all binomials (and as such is frequency independent). However, they demonstrated that by adding a regularization parameter, the model predicts frequency-dependent preference extremity. This parameter pressures productions to be more regular (regardless of the frequency of the binomial). For low-frequency binomials, the strength of the regularization is not strong enough to overcome the prior, and thus learners don't develop strong preferences for low-frequency binomials. On the other hand, high-frequency binomials occur enough that the regularization bias can overcome the prior and thus learners learn more polarized preferences (sometimes even in the opposite direction from the abstract preferences). In other words, this model was able to predict frequency-dependent preference extremity arising across generations of learners.

A visualization of their results is shown in Figure 1.1. The results demonstrate that as R increases (i.e., as the regularization parameter increases), the strength of the regularization effect increases (as demonstrated by greater probability density around values of 0 and 1). While their

---

[4]Note that α is specified a-priori and determines the shape of the beta distribution. Further, since the Bernoulli likelihood and the Beta prior form a conjugate pair, the resulting posterior is technically also a Beta distribution; Reali & Griffiths (2009).

results demonstrate that a frequency-independent regularization bias can account for frequency-dependent preference extremity, it's unclear what process this bias is analogous to in language learning/processing.

Figure 1.1: Visualization of results reproduced from Morgan & Levy (2016b). R indicates the regularization bias, ν indicates strength of the prior. The x-axis indicates the predicted ordering preference, with zero being a strong preference for the nonalphabetical ordering and 1 being a strong preference for the alphabetical ordering. Y-axis is the probability density. The results demonstrate that their model predicts polarized preferences for some binomials (i.e., increase in probability density for predicted ordering preferences near 0 and 1).
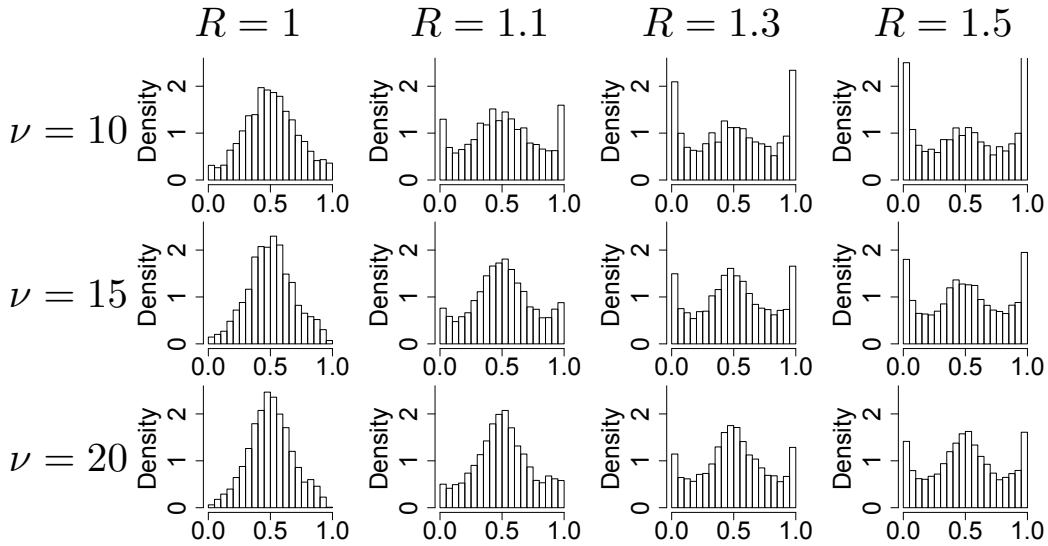
1.2. Noisy-channel Processing

One possibility is that the frequency-independent regularization bias is a consequence of noisy-channel processing.[5]

When processing language, we are faced with a great deal of noise in our environment. This can be literal noise in our environment, such as the sound of a loud city, or noise introduced by a communication device, such as static in a cellphone conversation. It can also be errors made by

---

[5]It is worth mentioning here that in parallel to the development of noisy-channel processing theories, other accounts making similar claims also emerged (e.g., Ferreira & Patson, 2007). Many of these theories accept that language processing must allow for flexibility and it's often difficult to disentangle them. While we take a noisy-channel approach in the present thesis, all of the claims we make are also compatible with good-enough processing theories as well, and we leave the task of disentangling the two theories to future work.

the speaker (speech errors) or by the listener (perceptual errors). Despite the abundance of noise in both our environment and in the input, the language processing system appears to be quite robust to noise. One possible explanation is that people may be tracking, not simply what they are hearing, but also what they think the speaker actually intended to say (Gibson et al., 2013; Levy, 2008). Thus in some cases where people hear something implausible, they may actually think that the speaker intended to say something else, and process it as if they did say the intended utterance.

There is a great deal of evidence that people do take noise into account. First and most obviously, when a listener misses a word due to simply not hearing it (e.g., a loud noise interrupted the utterance), it very rarely causes a complete breakdown in communication. Further, Ganong (1980) demonstrated that people process a non-word as being a word under noisy conditions. Similarly, Albert Felty et al. (2013) found that when listeners misperceive a word, the word that they believed to have heard is a higher frequency than the word spoken. These results suggest that in noise listeners are relying on information about the language, such as what utterances are more probable, to overcome the perceptual difficulties.

Interestingly, people will sometimes even hear a grammatical sentence and interpret the meaning differently from what they have heard due to noisy-channel processing. For example Christianson et al. (2001) found that when people read the sentence *While the man hunted the deer ran into the woods*, people will answer in the affirmative for the question *Did the man hunt the deer?* as well as the question *Did the deer run into the woods?*. People interpret this sentence as having been *While the man hunted the deer, it ran into the woods.* Levy (2008) argued that since both interpretations can arise from a single insertion, noisy-channel processing offers an explanation for this finding.

Following this, Gibson et al. (2013) formalized a noisy-channel processing model using a Bayesian framework. They modeled noisy-channel processing as a process wherein the listener estimates the probability of the speaker's intended utterance (s_i) given what they perceived (s_p, Equation 3) Specifically, the listener is modeled as a rational Bayesian who estimates the probability of the speaker's intended utterance given the perceived utterance as being proportional to the probability of the intended utterance in general times the probability of that perceived utterance given the intended utterance. This is formalized mathematically in Equation 3 where s_i is the

speaker's intended sentence and s_p is the perceived sentence. The prior $(P(s_p|s_i))$ is the probability of the intended sentence (s_i) being corrupted to the perceived sentence (s_p).

$$P(s_i|s_p) \propto P(s_i)P(s_p|s_i) \tag{3}$$

The model in Gibson et al. (2013) makes several predictions. For one, their model predicts that comprehenders should be more likely to interpret a semantically implausible sentence (e.g., *the mother gave the candle the daughter*) as being plausible (e.g., *the mother gave the candle to the daughter*) if there is increased noise because an increase in noise results in a greater probability that a plausible sentence was corrupted by noise (i.e., an increase in noise results in an increase in the value of $P(s_p = \text{implausible}|s_i = \text{plausible})$). Their model also predicts that increasing the probability of an implausible utterance should lead to an increased rate of implausible interpretations because by increasing the probability of an implausible utterance, the probability that the speaker intended to say an implausible utterance also increases (i.e., an increase in the value of $P(s_i = \text{implausible})$).

Gibson et al. (2013) tested these predictions by giving participants a series of sentences, some of which were semantically implausible but had semantically plausible alternatives that participants could interpret the sentence as being. These alternatives varied in how different they were from the perceived utterances. Some of them varied from the perceived utterance by a single insertion or a single deletion, while others varied by two insertions or two deletions. In order to test their first prediction, they increased the noise by manipulating the number of filler items with syntactic errors. They found that their model's first prediction was borne out: participants were more likely to interpret the semantically implausible sentence as being plausible. In order to test their second prediction, they also manipulated the probability of an implausible utterance by increasing the number of implausible sentences in the filler items. They found that their model's second prediction was also borne out: participants were more likely to interpret the implausible sentences as being implausible.

Given these results, Houghton & Morgan (2024) extended Morgan & Levy (2016b)'s model to examine whether a noisy-channel processing model integrated with an iterated learn-

ing model can account for frequency-dependent preference extremity. Specifically, we used a 2-alternative iterated learning paradigm. In this paradigm, learners are modeled as having heard N tokens of a given binomial in either alphabetical or nonalphabetical order while updating their hypothesis about the probability of each ordering of the binomial. In our model, the learner's goal was to learn the ordering preferences for each binomial. After learning the ordering preferences for each binomial, the learner then produced N tokens to the next generation. This process then repeated iteratively.

After hearing a binomial, the learner in our model updated their beliefs in proportion to how probable they believed the speaker's intended ordering was (calculated using Equation 3), which was modeled with pseudo counts. For example, if they believed the intended utterance was *A and B* with 60% probability and *B and A* with 40% probability, then they would add 0.6 and 0.4 to the pseudo counts for *A and B* and *B and A* respectively.[6]

To help build intuition for this: suppose a learner believes there is a 60% chance that the speaker intended to say *A and B*, but they heard *B and A*. Without a noisy-channel processing component, the learner would update their belief, down-weighting the probability of *A and B* and up-weighting the probability of *B and A* (because they heard *B and A*). However, in our model, the learner may actually assume the speaker intended to say *A and B* (after calculating this probability according to Equation 3), but had actually misspoken and said *B and A*. This would then result in updating their beliefs as if they had heard *A and B* (or more accurately, in proportion to the learner's belief about the probability that the speaker intended *A and B*). For high-frequency binomials, the learner encounters the binomial more and has more opportunities to update their ordering preferences, which may result in the learner developing more polarized preferences for that binomial. However, for low-frequency binomials, the learner does not encounter the binomial as many times and has fewer opportunities to update their beliefs, which may result in less polarized preferences.

In Houghton & Morgan (2024), we tested whether this model can account for frequency-dependent preference extremity and found that it can. Specifically, we found that for

---

[6]See Houghton & Morgan (2024) for a more detailed explanation of our computational model.

low-frequency binomials, the learner's belief about the intended ordering was not particularly strong. However, for high-frequency binomials, as the language was transmitted across generations, high-frequency binomials developed polarized preferences (i.e., frequency-dependent preference extremity).

Our results in Houghton & Morgan (2024) are illustrated in Figure 1.2. The plot demonstrates that as the overall frequency of the binomial increases (N), the inferred binomial ordering preferences become more polarized (i.e., closer to zero or one). This plot demonstrates that the model in Houghton & Morgan (2024) is able to capture the effects of frequency-dependent preference extremity.

Altogether, the results in Houghton & Morgan (2024) suggested that a noisy-channel processing model integrated with an iterative learning paradigm may account for the emergence of frequency-dependent preference extremity (though only when the listener infers more noise than the speaker is actually producing). The model also makes a crucial prediction: that learners sometimes hear *B and A*, but actually interpret it to be *A and B*. In the present study we explore this prediction.

1.3. Present Thesis

The model in Houghton & Morgan (2024) predicts that learners sometimes hear one binomial ordering but interpret it to be the opposite ordering. If this is the case, then it is possible that upon hearing, e.g., *white and black*, the listener actually processes it as *black and white*. There is a great deal of evidence that activating a phrase results in decreased processing time if encountering the same phrase shortly after (e.g., repetition priming effects; Tabossi & Johnson-Laird, 1980). If this is the case, then hearing *white and black* should actually speed up the processing of *black and white* more than it speeds up the processing of *white and black*. This is the prediction that we set out to test in the present study.

Figure 1.2: A plot of the ordering preferences predicted by the model in Houghton & Morgan (2024). The values at the top indicate the frequency of the binomial (N). The y-axis indicates the probability density and the x-axis indicates the ordering preference. Thus values closer to 0 and 1 are more extreme ordering preferences. The plot demonstrates that as the frequency of the binomial increases, the predicted ordering preferences become more extreme. This pattern is also observed in the corpus data in Morgan & Levy (2015).
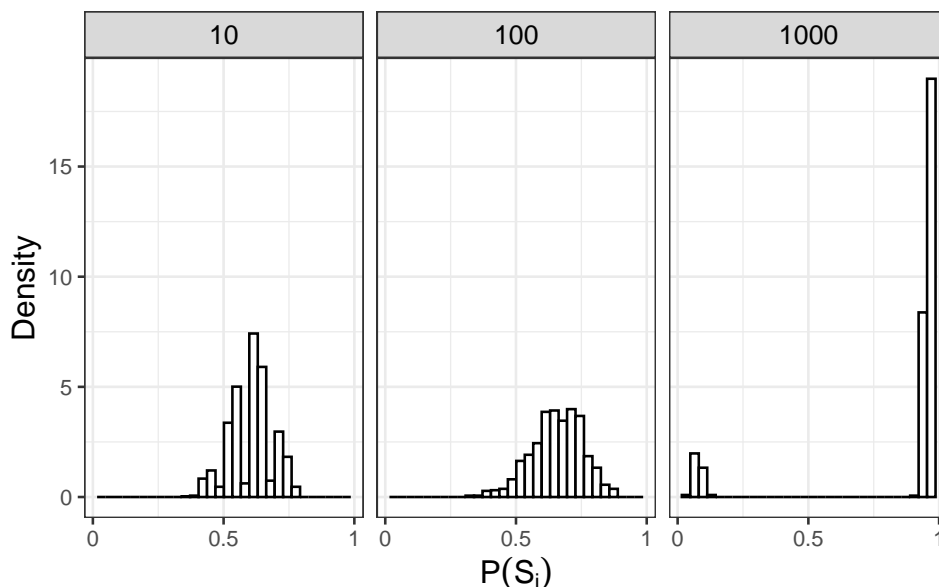
2. Methods

2.1. Procedure

In order to examine the effects of noisy-channel processing on the reading times of binomials, we used a primed self-paced reading task with a mental rotation task. Specifically, participants were first presented auditorily with a prime sentence while simultaneously completing a mental rotation task. The mental rotation task involved determining whether one image was a simple rotation or a mirror image of another image (We used images of the capital letter 'F'). The rotation was always either 0 degrees or 45 degrees. Participants were tasked with either pressing the 'f' key or the 'j' key to indicate that the image was either a simple rotation or a mirror image. The experiment was counterbalanced between experiments with respect to whether participants pressed 'f' to indicate that the image was a mirror image, or whether they pressed j' to. The reasoning behind the mental rotation task was to that forcing participants to complete an additional task

while listening to the prime sentence may encourage them to rely more on noisy-channel processing than if they could focus solely on the prime sentences. More specifically, completing two tasks simultaneously leads to less attention being allocated to the signal, which may encourage listeners to rely more on noisy-channel processing.

On each trial, after listening to the prime sentence and simultaneously completing the mental rotation, participants then completed a self-paced reading task. Specifically, participants were presented with a sentence word-by-word. After reading the word, they then pressed the 'space' key to proceed to the next word. Reaction times for the time it took participants to press the 'space' key were recorded for each word. After each sentence, participants were presented with a comprehension question to test their attention. The comprehension questions were questions either about the prime sentence or the sentence they had just read.

2.2. Stimuli

Our stimuli consisted of 30 polarized binomials.[7] Specifically, these were binomials that occurred more than 400,000 times (out of 323,592,921,465 tokens), calculated using the Google *n*-grams corpus (Michel et al., 2011). Additionally, all of our items had a relative frequency of either less than -0.30 and greater than 0.30. Relative frequency indicates which ordering is more preferred (and to what magnitude). For example, a binomial that occurs equally as many times in both orders would have a relative frequency of zero (where relative frequency ranges from -0.50 to 0.50). A relative frequency value below 0 indicates that the nonalphabetical ordering occurred more than the alphabetical ordering in corpus data, and a number above zero indicates the opposite. The magnitude of the number indicates the strength, with 0.50 indicating that the binomial occurred exclusively in alphabetical ordering and -0.50 indicated the binomial occurred exclusively in non-alphabetical ordering. Thus binomials with a relative frequency below -0.3 and above 0.3 are quite polarized in their ordering.

For each of these binomials, we created a prime and a target sentence containing the

---

[7]Our stimuli and analyses are available at the following link: https://github.com/znhoughton/Noisy-Channel-Binomial-Preferences. The stimuli are also included in the appendix section (Section A).

Table 2.1: A table of our conditions.

Condition	Target Freq.	Prime Freq.	Target Binomial	Prime Binomial
1	Infrequent	Infrequent	gentlemen and ladies	gentlemen and ladies
2	Frequent	Infrequent	ladies and gentlemen	gentlemen and ladies
3	Infrequent	Frequent	gentlemen and ladies	ladies and gentlemen
4	Frequent	Frequent	ladies and gentlemen	ladies and gentlemen
5	Infrequent	Unrelated	gentlemen and ladies	Unrelated
6	Frequent	Unrelated	ladies and gentlemen	Unrelated

binomial in either order. Specifically, for each binomial, one sentence was created that contained the binomial in either the frequent or infrequent order and another unrelated sentence that did not contain any binomial was made as a control. These priming conditions are referred to as the frequent, infrequent, and unrelated prime conditions respectively. We also made a target sentence (the sentences read during the self-paced reading task) that contained the binomial in either the frequent or infrequent ordering. A table demonstrating our six conditions is presented in Table 2.1. Finally, we also included 30 filler trials, which did not contain binomials in the prime or target sentences.

Our prime and target sentences were crossed such that each target occurred with each prime, however no participant was presented with the same binomial in more than one trial.

2.3. Participants

228 University of California, Davis undergraduate students were given course credit to participate in the study. We also recruited an additional 220 participants through Prolific. We then excluded participants based on their accuracy on the comprehension questions that asked about the prime sentences. Participants were randomly presented with one of 6 conditions. Since our design is a 3 x 2 design, 6 conditions were created so that participants did not encounter the same binomial in more than one trial.

For both analyses, participants were excluded for having an accuracy below 0.7 on the comprehension questions about the auditorily presented prime. 194 participants were excluded for having an accuracy below our threshold, leaving a total of 254 participants. Although this accuracy

cutoff resulted in a large number of participants being excluded, it is likely due to the difficulty of the task. The prime sentence was given to participants auditorily while they completed a mental rotation task. They then read a sentence in a self-paced reading task before answering the question about the prime.

2.4. Analysis

We divided the sentences into a single region which contained the three words of the binomial along with the 3 words following the binomial. We then excluded trials for which the reading times on this region were less than 100ms or greater than 5000ms (following Morgan & Levy, 2016a). We also excluded participants who had an average accuracy below 0.7 on the audio comprehension questions (the questions that asked about the auditorily presented prime).

Next we calculated residual reading times for each item. Residual reading times are a by-participant measure of reading times that take the effect of word length into account. Specifically, they are the residual error of a linear regression model that regresses reading time by word length for each participant (calculated using data from all non-sentence-final words in non-practice trials following Morgan & Levy, 2016a). We then summed the residual reading times for each word in the 6-word region to get a single residual reading time score for each sentence. Finally, we excluded trials for which the residual reading times were outside of 2.5 standard deviations from the mean.

We then ran two Bayesian mixed-effects regression models with residual reading times as the dependent variable.[8]

For the first model, we were interested in the effect of the frequent prime on the residual reading times of the frequent and infrequent orderings for each binomial. As such, we filtered the dataframe to include trials that contained either an unrelated or frequent prime. We then treatment coded our variables such that for the prime sentences, 0 indicated an unrelated prime and 1 indicated a frequent prime. For target sentences, 0 indicated an infrequent target while 1 indicated

---

[8]A pre-registration of our study is available at the following link: https://aspredicted.org/t324-swgk.pdf.

a frequent target. We then ran a model with residual reading time as the dependent variable, fixed-effects for prime, target, and their interaction, as well as maximal random-effects (following Barr et al., 2013).

Our second model was similar, however we were interested in the effect of infrequent primes on residual reading times. As such, we filtered our dataframe to include trials that contained either the unrelated or infrequent prime. We then treatment coded our variables such that 0 indicated an unrelated prime and 1 indicated an infrequent prime. Our model syntax was the same for both models, as mentioned previously the difference was the levels of the variables included in the data.

$$\text{Residual Reading Time} \sim \text{Intercept} + \text{prime freq} * \text{target freq}$$
$$+ (\text{prime freq} * \text{target freq}|\text{Item}) + (\text{prime freq} * \text{target freq}|\text{participant})$$
$$(4)$$

3. Results

We first examined whether a frequent prime facilitated the reading of the frequent ordering of the binomial more than the reading time of the infrequent ordering. Following Houghton et al. (2024), in addition to reporting the estimates we also report the percentage of posterior samples greater than zero. Bayesian statistics don't force us into a binary interpretation of significance or non-significance; by reporting the percentage of posterior samples greater than zero we are able to interpret the results in a more nuanced manner.

In both analyses, the mean accuracy on the audio comprehension questions was 85% and the mean accuracy on all comprehension questions was ~96%. Additionally, mean accuracy on the mental rotation task was ~94%. Interestingly, there was no real difference in accuracy scores for mental rotation trials where the angle was 0 degrees (94.7% accuracy) and trials where the angle was 45 degrees (93.6%).[9]

---

[9]In previous pilot versions of the experiment, we made the mental rotation task harder. However, the increase in

Table 3.1: Results of the statistical model for the frequent vs unrelated prime.

	Estimate	Est.Error	Q2.5	Q97.5	% Samples > 0
Intercept	-169.01	20.59	-209.40	-128.03	0.00
Frequent Prime	25.76	17.04	-7.10	59.63	93.92
Frequent Target	-25.70	15.09	-56.01	3.41	4.32
Frequent Prime:Frequent Target	-23.91	19.30	-63.64	12.47	10.19

The results are presented in Table 3.1 and visualized in Figure 3.1. In our first analysis, since prime and target types were treatment coded, the Intercept represents the estimated reading times for unrelated prime sentences with an infrequent target sentence. Coefficient estimates represent the distance from the Intercept. Although the credible interval crosses zero, over 93% of the posterior samples for the effect of frequent prime were greater than zero, suggesting that for not-frequent targets, the frequent prime resulted in slower reading times than the unrelated prime. Similarly, over 93% of the posterior samples for frequent target were less than zero, suggesting that for unrelated primes, the frequent target was read faster. Finally, about 90% of the samples for the interaction effect were less than zero, suggesting that the difference between the reading times in the unrelated prime condition and the reading times in the frequent prime condition were larger for infrequent targets than frequent targets. In other words, the frequent prime speeds up the reading times for the frequent ordering of the binomial more than it speeds up the infrequent ordering of the binomial.

Next we examined whether the infrequent prime speeds up the reading time of the infrequent ordering of the binomial more than it speeds up the reading time of the frequent ordering. If readers are engaged in noisy-channel processing when listening to the prime, they may actually activate *bread and butter* when they hear *butter and bread*. This would result in the infrequent prime speeding up the *frequent* ordering of the binomial more than the infrequent ordering.

The results are presented in Table 3.2 and visualized in Figure 3.1. Similar to the previous model, since prime and target types were treatment coded, the Intercept represents the estimated reading times for unrelated prime sentences with an infrequent target sentence. Coefficient estimates represent the distance from the Intercept. We find no meaningful main-effect for infrequent

---

difficulty eliminated the priming effect (possibly because participants had to allocate more attentional resources to the rotation task). Therefore we opted for an easier mental rotation task, hence the high accuracy scores.

Table 3.2: Results of the statistical model for the infrequent vs unrelated prime.

	Estimate	Est.Error	Q2.5	Q97.5	% Samples > 0
Intercept	-173.52	20.78	-214.07	-132.06	0.00
Infrequent Prime	7.48	14.00	-19.71	35.31	70.50
Frequent Target	-13.94	14.61	-43.68	13.84	16.81
Infrequent Prime:Frequent Target	24.57	19.39	-11.57	64.51	90.53

primes or frequent targets, but we do find a meaningful interaction effect. While the credible interval crosses zero, over 90% of the posterior samples were greater than zero. The results suggest that the infrequent prime speeds up the reading of the infrequent target more than the frequent target.

Figure 3.1: Plot of our model estimates. The x-axis represents whether the prime was unrelated, frequent, or infrequent. The y-axis corresponds to the residual reading times. Color indicates whether the target was infrequent (green) or frequent (blue). The left plot compares the unrelated primes to frequent primes, the right plot compares the unrelated primes to infrequent primes. The result suggest that the primed ordering is read faster regardless of whether the primed binomial ordering is frequent or infrequent.
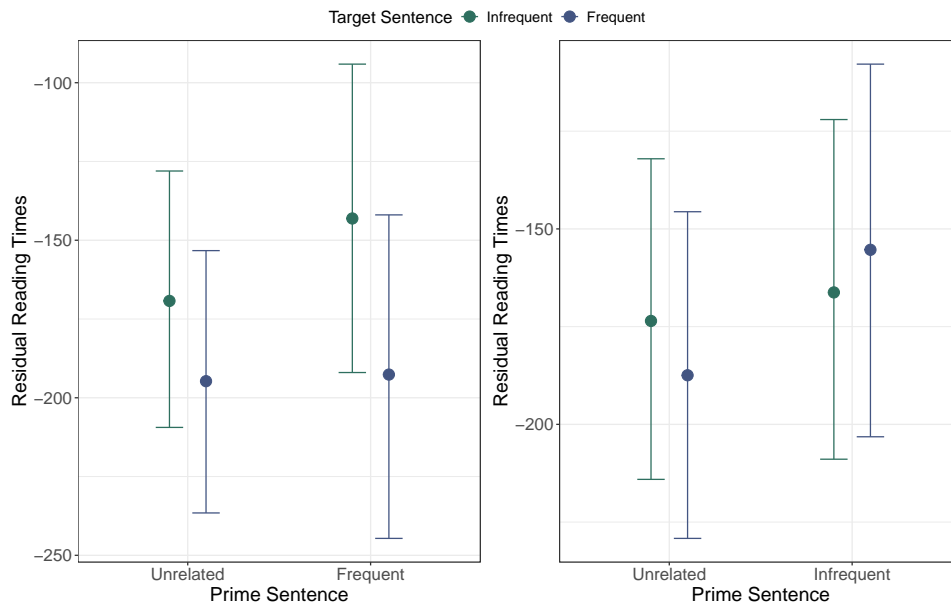
4. Discussion

Our results demonstrate that both the frequent and infrequent ordering of a given binomial speed up the reading times of the respective ordering. That is, priming the frequent ordering

speeds up the reading of the frequent ordering, and priming the infrequent ordering speeds up the reading of the infrequent ordering.

Our model in Houghton & Morgan (2024) predicted the opposite result, that hearing the infrequent binomial ordering might actually result in learner's accessing the frequent ordering of the binomial. The model makes two assumptions that are crucial to the present study. First, the model assumes that both the frequent and infrequent ordering are stored holistically. That is, it assumes that both *bread and butter* and *butter and bread* are stored holistically. Second, the model assumes that noisy-channel processing can cause the listener to hear one ordering but assume that the speaker's intended utterance was actually the opposite ordering.

With respect to the first assumption, it is certainly possible that both orderings are stored holistically (e.g., Ambridge, 2020). However, it is also possible that only the frequent orderings for polarized binomials are stored holistically. Indeed, a great deal of the evidence for stored items suggests that frequency drives holistic storage (Arnon & Snider, 2010; Bybee, 2003; Bybee & Scheibman, 1999; Kapatsinski & Radicke, 2009; Morgan et al., 2023; Morgan & Levy, 2016a, 2024). It is possible that noisy-channel processing interacts with multi-word holistically stored items differently than with multi-word items that aren't stored holistically. For example, there is evidence that holistically stored phrases "fuse" together (Kapatsinski & Radicke, 2009). It is also the case that holistically stored multi-morphemic words are less susceptible to speech errors (Stemberger & MacWhinney, 2004). Given these results, a holistically stored binomial such as *bread and butter* may not be as susceptible to the same substitution errors that would lead to a speaker producing the speech error *butter and bread*. Listeners may be sensitive to this and thus may not believe that it is a probable speech error.

Alternatively, it's possible that the results we see here are independent of the holistic storage of binomials. For example, perhaps noisy-channel processing occurs at a higher-level than priming does, potentially occurring after the acoustics for the binomial have been processed. In this scenario, while the listener may hear *butter and bread* and interpret the sentence as containing the frequent ordering of the binomial, it does not undo the fact that they heard the acoustics of *butter and bread*. Priming may be lower-level and thus simply hearing the acoustics may result in

the priming of *butter and bread* more than *bread and butter*. Even after noisy-channel processing activates the alternative lexical representation, it may not feed back down into the phonological activations of the listener, hence the lack of a difference in priming.

On the other hand, it is also possible people aren't even interpreting *butter and bread* as *bread and butter* in the first place (i.e., it is possible that binomials are not undergoing noisy-channel processing). There are a few possible explanations for why this might be. The first possibility is that hearing polarized binomials in the infrequent ordering is quite surprising. If the listener is expecting *bread and butter*, then hearing *butter and bread* may draw attention to the binomial, and thus the listener may be confident that they did infact hear *butter and bread*. This confidence would prevent the listener from interpreting the binomial as the more frequent ordering, explaining why there is no priming of *bread and butter*. Indeed, there is evidence in the literature that prediction error (i.e., violation of expectations/prediction) leads to both enhanced memory and better learning due to increased attention to the surprising item (Haeuser & Kray, 2023; Hollingworth & Henderson, 2000; Hubbard & Federmeier, 2024; Olejarczuk et al., 2018). For example, Haeuser & Kray (2023) used a self-paced reading task followed by a word recognition task to examine the role of prediction in memory. They found that when participants showed larger effects of prediction error (i.e., greater residual reading time differences between unpredictable and predictable items), they also showed enhanced memory effects (i.e., better performance in the word recognition task). In other words, when participants' expectations were violated, they were able to remember the word better. Further, there is also evidence that surprising objects in a scene attract attention and tend to be remembered better (Hollingworth & Henderson, 2000). For example, Hollingworth & Henderson (2000) found that participants were able to more quickly identify whether an object was in a previous scene if that object was semantically inconsistent (i.e., surprising) with the other objects in the scene. These results in conjunction with the present study suggest that it is possible that the surprising nature of the infrequent ordering of the binomials draws enough attention to them to negate any noisy-channel processing effects.

It's also possible that the size of the units matter. Much of the literature on noisy-channel processing involves short prepositions being inserted or deleted. However in our case, many of the binomials are multi-syllabic. It is possible that listeners are more likely to assume that the speaker

forgot to say a preposition, such as *in* or *up*, than to assume that the speaker accidentally swapped two multi-syllabic words (e.g., in the case of *gentlemen and ladies* instead of *ladies and gentlemen*). On the other hand, there is evidence that people do interpret semantically implausible sentences as being semantically plausible even if the semantically plausible interpretation requires positing a substitution (Poppels & Levy, 2016). Further, word and phrase exchanges are a very common type of speech error (Fromkin & Fromkin, 1973), so a robust system of language processing should be able to account for these types of errors without incurring too much of a cost. However, it is still the case that the prepositions used in Poppels & Levy (2016) were short prepositions as well. As such, it is possible that the size of the units plays a role in how willing the listener is to assume that the speaker misspoke, or to assume that the listener misheard.

Finally, it's possible that semantic plausibility also plays a large role in noisy-channel processing. That is, both orders of binomials are semantically plausible. It is simply the case that one is more frequent than the other. Further, while some high-frequency binomials have an idiomatic meaning (e.g., *bread and butter* meaning something that is easy/routine for someone), the sentences in the present study encouraged a compositional reading (since the sentences had to be compatible with both orderings of the binomial). It is possible that semantic implausibility is a pre-requisite to noisy-channel processing, even if an utterance is low-frequency. Perhaps in sentences that encourage an idiomatic reading, participants would be more likely to use noisy-channel processing. Even if not a pre-requisite, it seems plausible that implausibility may at least be a strong cue for noisy-channel processing (perhaps stronger than the form-based implausibility generated by *butter and bread*).

If frequency-dependent preference extremity isn't a result of noisy-channel processing, however, then how does frequency-dependent preference extremity arise? One possibility is that frequency-dependent preference extremity may be a result of accessibility effects. For example, there is evidence from the learning literature that people will use a frequent form even more frequently simply because it is more accessible (Harmon & Kapatsinski, 2017). For high-frequency binomials, if one ordering is more frequent than the other ordering, it may become more accessible than the infrequent ordering. Over time, this increase my compound resulting in the more frequent ordering being used increasingly more often (i.e., frequency-dependent preference extremity). On

the other hand, in the case of lower-frequency binomials, even if one ordering is more frequent, it may not occur often enough to result in a similar increase in accessibility.

In summary, the present results demonstrate that the ordering of a binomial primes the same ordering of the binomial without priming the opposite ordering. Further, this is the case regardless of whether it is the frequent ordering or the infrequent ordering that is primed. This is unexpected if noisy-channel processing results in listeners interpreting the infrequent ordering (e.g., *butter and bread*) as the frequent ordering (e.g., *bread and butter*). It is possible that either noisy-channel processing happens at a higher level, or that frequency-dependent preference extremity of binomials is not a consequence of noisy-channel processing, but rather a consequence of other mechanisms, such as a consequence of accessibility.

References

Albert Felty, R., Buchwald, A., Gruenenfelder, T. M., & Pisoni, D. B. (2013). Misperceptions of spoken words: Data from a random sample of american english words. *The Journal of the Acoustical Society of America*, *134*(1), 572–585.

Ambridge, B. (2020). Against stored abstractions: A radical exemplar model of language acquisition. *First Language*, *40*(5-6), 509–559. https://doi.org/10.1177/0142723719869731

Arnon, I., & Snider, N. (2010). More than words: Frequency effects for multi-word phrases. *Journal of Memory and Language*, *62*(1), 67–82. https://doi.org/10.1016/j.jml.2009.09.005

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Benor, S. B., & Levy, R. (2006). The chicken or the egg? A probabilistic analysis of english binomials. *Language*, *82*(2), 233–278. https://doi.org/10.1353/lan.2006.0077

Bybee, J. (2002). Word frequency and context of use in the lexical diffusion of phonetically conditioned sound change. *Language Variation and Change*, *14*(3), 261–290. https://doi.org/10.1017/S0954394502143018

Bybee, J. (2003). *Phonology and language use* (Vol. 94). Cambridge University Press. https://books.google.com/books?hl=en&lr=&id=IM2rnd-Hw14C&oi=fnd&pg=PP15&dq=bybee+2003+phonology&ots=oIS3kjcs8C&sig=xTECvGoj0XT_p39S36F9vIzQE5E

Bybee, J., & Scheibman, J. (1999). The effect of usage on degrees of constituency: The reduction of don't in english. *Linguistics*, *37*(4). https://doi.org/10.1515/ling.37.4.575

Chomsky, N. (1965). *Aspects of the theory of syntax special technical report no. 11*. https://ntrs.nasa.gov/api/citations/19670002070/downloads/19670002070.pdf

Christianson, K., Hollingworth, A., Halliwell, J. F., & Ferreira, F. (2001). Thematic roles assigned along the garden path linger. *Cognitive Psychology*, *42*(4), 368–407. https://doi.org/10.1006/cogp.2001.0752

Culicover, P. W., Jackendoff, R., & Audring, J. (2017). Multiword Constructions in the Grammar. *Topics in Cognitive Science*, *9*(3), 552–568. https://doi.org/10.1111/tops.12255

Ferreira, F., & Patson, N. D. (2007). The 'Good Enough' Approach to Language Comprehension. *Language and Linguistics Compass*, *1*(1-2), 71–83. https://doi.org/10.1111/j.1749-818X.2007.00007.x

Frazier, L., Munn, A., & Clifton, C. (2000). Processing coordinate structures. *Journal of Psycholinguistic Research*, *29*, 343370. https://idp.springer.com/authorize/casa?redirect_uri=https://link.springer.com/article/10.1023/A:1005156427600&casa_token=aXa9mHsTf20AAAAA:1tr8BkQQLq2fiFo3GrTfHDY1ole1ReP9SnnN54mGnGvfriCnmSHeeZZIHEpcbV419mhIvigcaZuIabY

Fromkin, V., & Fromkin, V. (1973). *Speech errors as linguistic evidence*. Mouton The Hague.

Ganong, W. F. (1980). Phonetic categorization in auditory word perception. *Journal of Experimental Psychology: Human Perception and Performance*, *6*(1), 110. https://psycnet.apa.org/record/1981-07020-001

Gibson, E., Piantadosi, S. T., Brink, K., Bergen, L., Lim, E., & Saxe, R. (2013). A noisy-channel account of crosslinguistic word-order variation. *Psychological Science*, *24*(7), 1079–1088. https://doi.org/10.1177/0956797612463705

Haeuser, K. I., & Kray, J. (2023). Effects of prediction error on episodic memory retrieval: Evidence from sentence reading and word recognition. *Language, Cognition and Neuroscience*, *38*(4), 558–574.

Harmon, Z., & Kapatsinski, V. (2017). Putting old tools to novel uses: The role of form accessibility in semantic extension. *Cognitive Psychology*, *98*, 22–44. https://doi.org/10.1016/j.cogpsych.2017.08.002

Hollingworth, A., & Henderson, J. M. (2000). Semantic informativeness mediates the detection of changes in natural scenes. *Visual Cognition*, *7*(1-3), 213–235.

Houghton, Z. N., Kato, M., Baese-Berk, M., & Vaughn, C. (2024). Task-dependent consequences of disfluency in perception of native and non-native speech. *Applied Psycholinguistics*, 1–17. https://doi.org/10.1017/S0142716423000486

Houghton, Z. N., & Morgan, E. (2023). Does predictability drive the holistic storage of compound nouns? *Proceedings of the Annual Meeting of the Cognitive Science Society*, *45*. https://escholarship.org/uc/item/7kz7w10b

Houghton, Z. N., & Morgan, E. (2024). Frequency-dependent preference extremity arises from

a noisy-channel processing model. *Proceedings of the Annual Meeting of the Cognitive Science Society, 46*. https://escholarship.org/uc/item/5bj443rz

Hubbard, R. J., & Federmeier, K. D. (2024). The impact of linguistic prediction violations on downstream recognition memory and sentence recall. *Journal of Cognitive Neuroscience, 36*(1), 1–23.

Hudson Kam, C. L., & Newport, E. L. (2005). Regularizing Unpredictable Variation: The Roles of Adult and Child Learners in Language Formation and Change. *Language Learning and Development, 1*(2), 151–195. https://doi.org/10.1080/15475441.2005.9684215

Kapatsinski, V., & Radicke, J. (2009). *Frequency and the emergence of prefabs: Evidence from monitoring. January 2009*, 499. https://doi.org/10.1075/tsl.83.14kap

Levy, R. (2008). *A noisy-channel model of human sentence comprehension under uncertain input*. 234243. https://aclanthology.org/D08-1025.pdf

Liu, Z., & Morgan, E. (2020). *Frequency-dependent regularization in constituent ordering preferences.* https://www.cognitivesciencesociety.org/cogsci20/papers/0751/0751.pdf

Liu, Z., & Morgan, E. (2021). *Frequency-dependent regularization in syntactic constructions*. 387389. https://aclanthology.org/2021.scil-1.41.pdf

McMurray, B., Aslin, R. N., Tanenhaus, M. K., Spivey, M. J., & Subik, D. (2008). Gradient sensitivity to within-category variation in words and syllables. *Journal of Experimental Psychology: Human Perception and Performance, 34*(6), 1609–1631. https://doi.org/10.1037/a0011747

Michel, J.-B., Shen, Y. K., Aiden, A. P., Veres, A., Gray, M. K., The Google Books Team, Pickett, J. P., Hoiberg, D., Clancy, D., Norvig, P., Orwant, J., Pinker, S., Nowak, M. A., & Aiden, E. L. (2011). Quantitative Analysis of Culture Using Millions of Digitized Books. *Science, 331*(6014), 176–182. https://doi.org/10.1126/science.1199644

Mollica, F., & Piantadosi, S. T. (2019). Humans store about 1.5 megabytes of information during language acquisition. *Royal Society Open Science, 6*(3), 181393. https://doi.org/10.1098/rsos.181393

Morgan, E., Ergin, R., & O'Donnell, T. J. (2023). *Formalizing theories of storage versus computation with tree-based grammars.*

Morgan, E., & Levy, R. (2015). *Modeling idiosyncratic preferences : How generative knowledge and expression frequency jointly determine language structure*. 1649–1654.

Morgan, E., & Levy, R. (2016a). Abstract knowledge versus direct experience in processing of binomial expressions. *Cognition, 157*, 384–402. https://doi.org/10.1016/j.cognition.2016.09.011

Morgan, E., & Levy, R. (2016b). Frequency-dependent regularization in iterated learning. *The Evolution of Language: Proceedings of the 11th International Conference*.

Morgan, E., & Levy, R. (2024). Productive knowledge and item-specific knowledge trade off as a function of frequency in multiword expression processing. *Language, 100*(4), e195–e224. https://muse.jhu.edu/pub/24/article/947046

Olejarczuk, P., Kapatsinski, V., & Baayen, R. H. (2018). Distributional learning is error-driven: The role of surprise in the acquisition of phonetic categories. *Linguistics Vanguard, 4*(s2), 1–9. https://doi.org/10.1515/lingvan-2017-0020

Pinker, S., & Ullman, M. T. (2002). The past and future of the past tense. *Trends in Cognitive Sciences, 6*(11), 456–463. https://doi.org/10.1016/S1364-6613(02)01990-3

Poppels, T., & Levy, R. (2016). *Structure-sensitive noise inference: Comprehenders expect exchange errors.* https://tpoppels.github.io/files/2016-poppels-levy-cogsci-proceedings.pdf

Reali, F., & Griffiths, T. L. (2009). The evolution of frequency distributions: Relating regularization to inductive biases through iterated learning. *Cognition, 111*(3), 317–328. https://doi.org/10.1016/j.cognition.2009.02.012

Siyanova-Chanturia, A., Conklin, K., & Heuven, W. J. B. van. (2011). Seeing a phrase "time and again" matters: The role of phrasal frequency in the processing of multiword sequences. *Journal of Experimental Psychology: Learning Memory and Cognition, 37*(3), 776–784. https://doi.org/10.1037/a0022531

Stemberger, J. P., & MacWhinney, B. (2004). Are inflected forms stored in the lexicon. *Morphology: Critical Concepts in Linguistics, 6*, 107122. https://books.google.com/books?hl=en&lr=&id=bGl0aKBld3cC&oi=fnd&pg=PA107&dq=stemberger+2004+inflected&ots=RdvzVaC_NS&sig=0DJV8gUVaoZv_COZqcLXOu5_evU

Tabossi, P., & Johnson-Laird, P. N. and. (1980). Linguistic context and the priming of semantic information. *Quarterly Journal of Experimental Psychology, 32*(4), 595–603. https://doi.org/10.1080/14640748008401848

Wang, Y., Liu, D., & Wang, Y. (2003). Discovering the Capacity of Human Memory. *Brain and Mind,*

4(2), 189–198. https://doi.org/10.1023/A:1025405628479

Yi, B. W. (2002). 음운 현상과 빈도 효과 *[the effect of usage frequency in phonology]*.

Appendix

A. Full List of Stimuli

Our full stimuli list is included below.

Table A.1: Full set of stimuli.

Binomial	RelFreq	GenPref	PrimeType	SentenceType	Sentence	Prime
gentlemen and ladies	-0.4086472	0.5176319	alphabetical	Sentence (alphabetical)	+ The hostess in the venue lead the gentlemen and ladies to their respective tables.	The event was attended by both gentlemen and ladies dressed in elegant attire.
gentlemen and ladies	-0.4086472	0.5176319	alphabetical	Sentence (nonalphabetical)	+ The hostess in the venue lead the ladies and gentlemen to their respective tables.	The event was attended by both gentlemen and ladies dressed in elegant attire.
gentlemen and ladies	-0.4086472	0.5176319	nonalphabetical	Sentence (alphabetical)	+ The hostess in the venue lead the gentlemen and ladies to their respective tables.	The event was attended by both ladies and gentlemen dressed in elegant attire.
gentlemen and ladies	-0.4086472	0.5176319	nonalphabetical	Sentence (nonalphabetical)	+ The hostess in the venue lead the ladies and gentlemen to their respective tables.	The event was attended by both ladies and gentlemen dressed in elegant attire.
gentlemen and ladies	-0.4086472	0.5176319	unrelated	Sentence (alphabetical)	+ The hostess in the venue lead the gentlemen and ladies to their respective tables.	The snow covered the town in a blanket of white, transforming it into a winter wonderland.
gentlemen and ladies	-0.4086472	0.5176319	unrelated	Sentence (nonalphabetical)	+ The hostess in the venue lead the ladies and gentlemen to their respective tables.	The snow covered the town in a blanket of white, transforming it into a winter wonderland.
fruits and vegetables	0.3501051	0.6085325	alphabetical	Sentence (alphabetical)	+ Growing up, Paul ate his fruits and vegetables everyday at each meal.	A healthy diet includes a balance of fruits and vegetables for essential nutrients.
fruits and vegetables	0.3501051	0.6085325	alphabetical	Sentence (nonalphabetical)	+ Growing up, Paul ate his vegetables and fruits everyday at each meal.	A healthy diet includes a balance of fruits and vegetables for essential nutrients.
fruits and vegetables	0.3501051	0.6085325	nonalphabetical	Sentence (alphabetical)	+ Growing up, Paul ate his fruits and vegetables everyday at each meal.	A healthy diet includes a balance of vegetables and fruits for essential nutrients.
fruits and vegetables	0.3501051	0.6085325	nonalphabetical	Sentence (nonalphabetical)	+ Growing up, Paul ate his vegetables and fruits everyday at each meal.	A healthy diet includes a balance of vegetables and fruits for essential nutrients.
fruits and vegetables	0.3501051	0.6085325	unrelated	Sentence (alphabetical)	+ Growing up, Paul ate his fruits and vegetables everyday at each meal.	The orchestra's music filled the hall, sending chills down the audience's spines.
fruits and vegetables	0.3501051	0.6085325	unrelated	Sentence (nonalphabetical)	+ Growing up, Paul ate his vegetables and fruits everyday at each meal.	The orchestra's music filled the hall, sending chills down the audience's spines.
blood and flesh	-0.4736040	0.4690761	alphabetical	Sentence (alphabetical)	+ Although Rhonda was not Nick's blood and flesh he considered her family.	The battle left marks of blood and flesh on the ground, a grim reminder of its toll.
blood and flesh	-0.4736040	0.4690761	alphabetical	Sentence (nonalphabetical)	+ Although Rhonda was not Nick's flesh and blood he considered her family.	The battle left marks of blood and flesh on the ground, a grim reminder of its toll.
blood and flesh	-0.4736040	0.4690761	nonalphabetical	Sentence (alphabetical)	+ Although Rhonda was not Nick's blood and flesh he considered her family.	The battle left marks of flesh and blood on the ground, a grim reminder of its toll.
blood and flesh	-0.4736040	0.4690761	nonalphabetical	Sentence (nonalphabetical)	+ Although Rhonda was not Nick's flesh and blood he considered her family.	The battle left marks of flesh and blood on the ground, a grim reminder of its toll.
blood and flesh	-0.4736040	0.4690761	unrelated	Sentence (alphabetical)	+ Although Rhonda was not Nick's blood and flesh he considered her family.	With a deep breath, she stepped onto the stage, her heart pounding in her chest.
blood and flesh	-0.4736040	0.4690761	unrelated	Sentence (nonalphabetical)	+ Although Rhonda was not Nick's flesh and blood he considered her family.	With a deep breath, she stepped onto the stage, her heart pounding in her chest.
father and son	0.4679236	0.5278980	alphabetical	Sentence (alphabetical)	+ Eric enjoys watching movies with his father and son so much that he goes often.	The bond between father and son grew deeper with each passing year.
father and son	0.4679236	0.5278980	alphabetical	Sentence (nonalphabetical)	+ Eric enjoys watching movies with his son and father so much that he goes often.	The bond between father and son grew deeper with each passing year.
father and son	0.4679236	0.5278980	nonalphabetical	Sentence (alphabetical)	+ Eric enjoys watching movies with his father and son so much that he goes often.	The bond between son and father grew deeper with each passing year.
father and son	0.4679236	0.5278980	nonalphabetical	Sentence (nonalphabetical)	+ Eric enjoys watching movies with his son and father so much that he goes often.	The bond between son and father grew deeper with each passing year.
father and son	0.4679236	0.5278980	unrelated	Sentence (alphabetical)	+ Eric enjoys watching movies with his father and son so much that he goes often.	The dog wagged its tail eagerly, hoping for a treat.
father and son	0.4679236	0.5278980	unrelated	Sentence (nonalphabetical)	+ Eric enjoys watching movies with his son and father so much that he goes often.	The dog wagged its tail eagerly, hoping for a treat.
place and time	-0.3613231	0.5553676	alphabetical	Sentence (alphabetical)	+ Finding a place and time for the meeting was very difficult.	Success in art depends on the right combination of place and time.
place and time	-0.3613231	0.5553676	alphabetical	Sentence (nonalphabetical)	+ Finding a time and place for the meeting was very difficult.	Success in art depends on the right combination of place and time.
place and time	-0.3613231	0.5553676	nonalphabetical	Sentence (alphabetical)	+ Finding a place and time for the meeting was very difficult.	Success in art depends on the right combination of time and place.
place and time	-0.3613231	0.5553676	nonalphabetical	Sentence (nonalphabetical)	+ Finding a time and place for the meeting was very difficult.	Success in art depends on the right combination of time and place.

place and time	-0.3613231	0.5553676	unrelated	Sentence (alphabetical)	+ Finding a place and time for the meeting was very difficult.	A gentle breeze rustled the leaves, carrying the scent of jasmine through the air.
place and time	-0.3613231	0.5553676	unrelated	Sentence (nonalphabetical)	+ Finding a time and place for the meeting was very difficult.	A gentle breeze rustled the leaves, carrying the scent of jasmine through the air.
arts and sciences	0.4544575	0.4933751	alphabetical	Sentence (alphabetical)	+ Jessica couldn't decide between studying arts and sciences at her time in college.	A well-rounded education often includes a balance of arts and sciences.
arts and sciences	0.4544575	0.4933751	alphabetical	Sentence (nonalphabetical)	+ Jessica couldn't decide between studying sciences and arts at her time in college.	A well-rounded education often includes a balance of arts and sciences.
arts and sciences	0.4544575	0.4933751	nonalphabetical	Sentence (alphabetical)	+ Jessica couldn't decide between studying arts and sciences at her time in college.	A well-rounded education often includes a balance of sciences and arts.
arts and sciences	0.4544575	0.4933751	nonalphabetical	Sentence (nonalphabetical)	+ Jessica couldn't decide between studying sciences and arts at her time in college.	A well-rounded education often includes a balance of sciences and arts.
arts and sciences	0.4544575	0.4933751	unrelated	Sentence (alphabetical)	+ Jessica couldn't decide between studying arts and sciences at her time in college.	The library was silent, except for the occasional sound of pages turning.
arts and sciences	0.4544575	0.4933751	unrelated	Sentence (nonalphabetical)	+ Jessica couldn't decide between studying sciences and arts at her time in college.	The library was silent, except for the occasional sound of pages turning.
development and research	-0.4807498	0.2293127	alphabetical	Sentence (alphabetical)	+ Emily was in development and research but eventually decided to leave.	Many years of development and research went into the company's new product.
development and research	-0.4807498	0.2293127	alphabetical	Sentence (nonalphabetical)	+ Emily was in research and development but eventually decided to leave.	Many years of development and research went into the company's new product.
development and research	-0.4807498	0.2293127	nonalphabetical	Sentence (alphabetical)	+ Emily was in development and research but eventually decided to leave.	Many years of research and development went into the company's new product.
development and research	-0.4807498	0.2293127	nonalphabetical	Sentence (nonalphabetical)	+ Emily was in research and development but eventually decided to leave.	Many years of research and development went into the company's new product.
development and research	-0.4807498	0.2293127	unrelated	Sentence (alphabetical)	+ Emily was in development and research but eventually decided to leave.	His suitcase was packed with essentials and a few souvenirs from his last adventure.
development and research	-0.4807498	0.2293127	unrelated	Sentence (nonalphabetical)	+ Emily was in research and development but eventually decided to leave.	His suitcase was packed with essentials and a few souvenirs from his last adventure.
law and order	0.4852173	0.8870849	alphabetical	Sentence (alphabetical)	+ There was a lack of law and order that caused some chaos.	The mayor promised to restore law and order to the troubled neighborhoods.
law and order	0.4852173	0.8870849	alphabetical	Sentence (nonalphabetical)	+ There was a lack of order and law that caused some chaos.	The mayor promised to restore law and order to the troubled neighborhoods.
law and order	0.4852173	0.8870849	nonalphabetical	Sentence (alphabetical)	+ There was a lack of law and order that caused some chaos.	The mayor promised to restore order and law to the troubled neighborhoods.
law and order	0.4852173	0.8870849	nonalphabetical	Sentence (nonalphabetical)	+ There was a lack of order and law that caused some chaos.	The mayor promised to restore order and law to the troubled neighborhoods.
law and order	0.4852173	0.8870849	unrelated	Sentence (alphabetical)	+ There was a lack of law and order that caused some chaos.	She took a long walk through the city, marveling at the towering skyscrapers.
law and order	0.4852173	0.8870849	unrelated	Sentence (nonalphabetical)	+ There was a lack of order and law that caused some chaos.	She took a long walk through the city, marveling at the towering skyscrapers.
mr. and mrs.	0.4980908	0.6408346	alphabetical	Sentence (alphabetical)	+ The couple call each other mr. and mrs. Smith even though they aren't married.	The invitation was addressed to Mr. and Mrs. Peterson, inviting them to the gala.
mr. and mrs.	0.4980908	0.6408346	alphabetical	Sentence (nonalphabetical)	+ The couple call each other mrs. and mr. Smith even though they aren't married.	The invitation was addressed to Mr. and Mrs. Peterson, inviting them to the gala.
mr. and mrs.	0.4980908	0.6408346	nonalphabetical	Sentence (alphabetical)	+ The couple call each other mr. and mrs. Smith even though they aren't married.	The invitation was addressed to Mrs. and Mr. Peterson, inviting them to the gala.
mr. and mrs.	0.4980908	0.6408346	nonalphabetical	Sentence (nonalphabetical)	+ The couple call each other mrs. and mr. Smith even though they aren't married.	The invitation was addressed to Mrs. and Mr. Peterson, inviting them to the gala.
mr. and mrs.	0.4980908	0.6408346	unrelated	Sentence (alphabetical)	+ The couple call each other mr. and mrs. Smith even though they aren't married.	They watched the fireworks explode in the night sky, their faces lit up with excitement.
mr. and mrs.	0.4980908	0.6408346	unrelated	Sentence (nonalphabetical)	+ The couple call each other mrs. and mr. Smith even though they aren't married.	They watched the fireworks explode in the night sky, their faces lit up with excitement.
men and women	0.4064281	0.7288978	alphabetical	Sentence (alphabetical)	+ Jen thought that the men and women in her dance class were all very talented.	The disparity between the wages of men and women in the workforce is a major concern for many.
men and women	0.4064281	0.7288978	alphabetical	Sentence (nonalphabetical)	+ Jen thought that the women and men in her dance class were all very talented.	The disparity between the wages of men and women in the workforce is a major concern for many.
men and women	0.4064281	0.7288978	nonalphabetical	Sentence (alphabetical)	+ Jen thought that the men and women in her dance class were all very talented.	The disparity between the wages of men and women in the workforce is a major concern for many.
men and women	0.4064281	0.7288978	nonalphabetical	Sentence (nonalphabetical)	+ Jen thought that the women and men in her dance class were all very talented.	The disparity between the wages of men and women in the workforce is a major concern for many.
men and women	0.4064281	0.7288978	unrelated	Sentence (alphabetical)	+ Jen thought that the men and women in her dance class were all very talented.	The cafe was cozy, with soft music playing and the smell of fresh pastries in the air.

men and women	0.4064281	0.7288978	unrelated	Sentence (nonalphabetical)	+ Jen thought that the women and men in her dance class were all very talented.	The cafe was cozy, with soft music playing and the smell of fresh pastries in the air.
money and time	-0.3966303	0.3490212	alphabetical	Sentence (alphabetical)	+ The amount of money and time required to fix it made it quite the project.	Managing money and time effectively is key to achieving financial goals.
money and time	-0.3966303	0.3490212	alphabetical	Sentence (nonalphabetical)	+ The amount of time and money required to fix it made it quite the project.	Managing money and time effectively is key to achieving financial goals.
money and time	-0.3966303	0.3490212	nonalphabetical	Sentence (alphabetical)	+ The amount of money and time required to fix it made it quite the project.	Managing time and money effectively is key to achieving financial goals.
money and time	-0.3966303	0.3490212	nonalphabetical	Sentence (nonalphabetical)	+ The amount of time and money required to fix it made it quite the project.	Managing time and money effectively is key to achieving financial goals.
money and time	-0.3966303	0.3490212	unrelated	Sentence (alphabetical)	+ The amount of money and time required to fix it made it quite the project.	She wrapped the scarf around her neck, bracing herself against the winter chill.
money and time	-0.3966303	0.3490212	unrelated	Sentence (nonalphabetical)	+ The amount of time and money required to fix it made it quite the project.	She wrapped the scarf around her neck, bracing herself against the winter chill.
brother and sister	0.3382719	0.6344815	alphabetical	Sentence (alphabetical)	+ Paul wants to spend time with his brother and sister because they are cool.	The brother and sister shared a bond that no distance could weaken.
brother and sister	0.3382719	0.6344815	alphabetical	Sentence (nonalphabetical)	+ Paul wants to spend time with his sister and brother because they are cool.	The brother and sister shared a bond that no distance could weaken.
brother and sister	0.3382719	0.6344815	nonalphabetical	Sentence (alphabetical)	+ Paul wants to spend time with his brother and sister because they are cool.	The sister and brother shared a bond that no distance could weaken.
brother and sister	0.3382719	0.6344815	nonalphabetical	Sentence (nonalphabetical)	+ Paul wants to spend time with his sister and brother because they are cool.	The sister and brother shared a bond that no distance could weaken.
brother and sister	0.3382719	0.6344815	unrelated	Sentence (alphabetical)	+ Paul wants to spend time with his brother and sister because they are cool.	The cat curled up on the windowsill, basking in a patch of warm sunlight.
brother and sister	0.3382719	0.6344815	unrelated	Sentence (nonalphabetical)	+ Paul wants to spend time with his sister and brother because they are cool.	The cat curled up on the windowsill, basking in a patch of warm sunlight.
husband and wife	0.4745981	0.5027550	alphabetical	Sentence (alphabetical)	+ Michelle was surprised to learn that the husband and wife were getting a divorce.	The couple was too young to be husband and wife, in their parents' opinion.
husband and wife	0.4745981	0.5027550	alphabetical	Sentence (nonalphabetical)	+ Michelle was surprised to learn that the wife and husband were getting a divorce.	The couple was too young to be husband and wife, in their parents' opinion.
husband and wife	0.4745981	0.5027550	nonalphabetical	Sentence (alphabetical)	+ Michelle was surprised to learn that the husband and wife were getting a divorce.	The couple was too young to be wife and husband, in their parents' opinion.
husband and wife	0.4745981	0.5027550	nonalphabetical	Sentence (nonalphabetical)	+ Michelle was surprised to learn that the wife and husband were getting a divorce.	The couple was too young to be wife and husband, in their parents' opinion.
husband and wife	0.4745981	0.5027550	unrelated	Sentence (alphabetical)	+ Michelle was surprised to learn that the husband and wife were getting a divorce.	The old house creaked and groaned with every gust of wind.
husband and wife	0.4745981	0.5027550	unrelated	Sentence (nonalphabetical)	+ Michelle was surprised to learn that the wife and husband were getting a divorce.	The old house creaked and groaned with every gust of wind.
north and south	0.4390121	0.6108187	alphabetical	Sentence (alphabetical)	+ The family moved north and south a couple of times.	The campaign has supporters from both north and south regions.
north and south	0.4390121	0.6108187	alphabetical	Sentence (nonalphabetical)	+ The family moved south and north a couple of times.	The campaign has supporters from both north and south regions.
north and south	0.4390121	0.6108187	nonalphabetical	Sentence (alphabetical)	+ The family moved north and south a couple of times.	The campaign has supporters from both south and north regions.
north and south	0.4390121	0.6108187	nonalphabetical	Sentence (nonalphabetical)	+ The family moved south and north a couple of times.	The campaign has supporters from both south and north regions.
north and south	0.4390121	0.6108187	unrelated	Sentence (alphabetical)	+ The family moved north and south a couple of times.	The antique store was filled with treasures from a bygone era.
north and south	0.4390121	0.6108187	unrelated	Sentence (nonalphabetical)	+ The family moved south and north a couple of times.	The antique store was filled with treasures from a bygone era.
error and trial	-0.4995134	0.1682363	alphabetical	Sentence (alphabetical)	+ Hal solved the math problem by error and trial because he was lazy.	Sometimes it feels like trial and error is the only way to learn.
error and trial	-0.4995134	0.1682363	alphabetical	Sentence (nonalphabetical)	+ Hal solved the math problem by trial and error because he was lazy.	Sometimes it feels like trial and error is the only way to learn.
error and trial	-0.4995134	0.1682363	nonalphabetical	Sentence (alphabetical)	+ Hal solved the math problem by error and trial because he was lazy.	Sometimes it feels like error and trial is the only way to learn.
error and trial	-0.4995134	0.1682363	nonalphabetical	Sentence (nonalphabetical)	+ Hal solved the math problem by trial and error because he was lazy.	Sometimes it feels like error and trial is the only way to learn.
error and trial	-0.4995134	0.1682363	unrelated	Sentence (alphabetical)	+ Hal solved the math problem by error and trial because he was lazy.	The aroma of freshly baked bread drifted from the kitchen, inviting everyone inside.
error and trial	-0.4995134	0.1682363	unrelated	Sentence (nonalphabetical)	+ Hal solved the math problem by trial and error because he was lazy.	The aroma of freshly baked bread drifted from the kitchen, inviting everyone inside.

black and white	0.3322019	0.4175274	alphabetical	Sentence (alphabetical)	+ Dalmatians found in colors other than black and white are really quite unusual.	The film is shot entirely in black and white, giving it a timeless quality.
black and white	0.3322019	0.4175274	alphabetical	Sentence (nonalphabetical)	+ Dalmatians found in colors other than white and black are really quite unusual.	The film is shot entirely in black and white, giving it a timeless quality.
black and white	0.3322019	0.4175274	nonalphabetical	Sentence (alphabetical)	+ Dalmatians found in colors other than black and white are really quite unusual.	The film is shot entirely in white and black, giving it a timeless quality.
black and white	0.3322019	0.4175274	nonalphabetical	Sentence (nonalphabetical)	+ Dalmatians found in colors other than white and black are really quite unusual.	The film is shot entirely in white and black, giving it a timeless quality.
black and white	0.3322019	0.4175274	unrelated	Sentence (alphabetical)	+ Dalmatians found in colors other than black and white are really quite unusual.	He watched the rain tap against the window, lost in thought.
black and white	0.3322019	0.4175274	unrelated	Sentence (nonalphabetical)	+ Dalmatians found in colors other than white and black are really quite unusual.	He watched the rain tap against the window, lost in thought.
arms and legs	0.3369926	0.6051687	alphabetical	Sentence (alphabetical)	+ Sandra broke her arms and legs because she got into a bike accident.	When he gets upset he crosses his arms and legs in a very tense manner.
arms and legs	0.3369926	0.6051687	alphabetical	Sentence (nonalphabetical)	+ Sandra broke her legs and arms because she got into a bike accident.	When he gets upset he crosses his arms and legs in a very tense manner.
arms and legs	0.3369926	0.6051687	nonalphabetical	Sentence (alphabetical)	+ Sandra broke her arms and legs because she got into a bike accident.	When he gets upset he crosses his legs and arms in a very tense manner.
arms and legs	0.3369926	0.6051687	nonalphabetical	Sentence (nonalphabetical)	+ Sandra broke her legs and arms because she got into a bike accident.	When he gets upset he crosses his legs and arms in a very tense manner.
arms and legs	0.3369926	0.6051687	unrelated	Sentence (alphabetical)	+ Sandra broke her arms and legs because she got into a bike accident.	The sun dipped below the horizon, painting the sky in shades of orange and pink.
arms and legs	0.3369926	0.6051687	unrelated	Sentence (nonalphabetical)	+ Sandra broke her legs and arms because she got into a bike accident.	The sun dipped below the horizon, painting the sky in shades of orange and pink.
arts and crafts	0.4952497	0.6080374	alphabetical	Sentence (alphabetical)	+ Lilly enjoys doing arts and crafts to relax when she is stressed.	Arts and crafts are a wonderful way to express creativity through handmade projects.
arts and crafts	0.4952497	0.6080374	alphabetical	Sentence (nonalphabetical)	+ Lilly enjoys doing crafts and arts to relax when she is stressed.	Arts and crafts are a wonderful way to express creativity through handmade projects.
arts and crafts	0.4952497	0.6080374	nonalphabetical	Sentence (alphabetical)	+ Lilly enjoys doing arts and crafts to relax when she is stressed.	Crafts and arts are a wonderful way to express creativity through handmade projects.
arts and crafts	0.4952497	0.6080374	nonalphabetical	Sentence (nonalphabetical)	+ Lilly enjoys doing crafts and arts to relax when she is stressed.	Crafts and arts are a wonderful way to express creativity through handmade projects.
arts and crafts	0.4952497	0.6080374	unrelated	Sentence (alphabetical)	+ Lilly enjoys doing arts and crafts to relax when she is stressed.	She poured herself a steaming cup of coffee, savoring the aroma as it filled the kitchen.
arts and crafts	0.4952497	0.6080374	unrelated	Sentence (nonalphabetical)	+ Lilly enjoys doing crafts and arts to relax when she is stressed.	She poured herself a steaming cup of coffee, savoring the aroma as it filled the kitchen.
goods and services	0.4925981	0.6638593	alphabetical	Sentence (alphabetical)	+ They would not trade goods and services even for a large sum of money.	The store offers a wide variety of goods and services to meet customer needs.
goods and services	0.4925981	0.6638593	alphabetical	Sentence (nonalphabetical)	+ They would not trade services and goods even for a large sum of money.	The store offers a wide variety of goods and services to meet customer needs.
goods and services	0.4925981	0.6638593	nonalphabetical	Sentence (alphabetical)	+ They would not trade goods and services even for a large sum of money.	The store offers a wide variety of services and goods to meet customer needs.
goods and services	0.4925981	0.6638593	nonalphabetical	Sentence (nonalphabetical)	+ They would not trade services and goods even for a large sum of money.	The store offers a wide variety of services and goods to meet customer needs.
goods and services	0.4925981	0.6638593	unrelated	Sentence (alphabetical)	+ They would not trade goods and services even for a large sum of money.	They toasted to friendship, clinking their glasses in celebration.
goods and services	0.4925981	0.6638593	unrelated	Sentence (nonalphabetical)	+ They would not trade services and goods even for a large sum of money.	They toasted to friendship, clinking their glasses in celebration.
feet and hands	-0.3822570	0.4219807	alphabetical	Sentence (alphabetical)	+ The child's feet and hands slowly grew very numb.	The dancer moved her feet and hands gracefully, commanding the stage.
feet and hands	-0.3822570	0.4219807	alphabetical	Sentence (nonalphabetical)	+ The child's hands and feet slowly grew very numb.	The dancer moved her feet and hands gracefully, commanding the stage.
feet and hands	-0.3822570	0.4219807	nonalphabetical	Sentence (alphabetical)	+ The child's feet and hands slowly grew very numb.	The dancer moved her hands and feet gracefully, commanding the stage.
feet and hands	-0.3822570	0.4219807	nonalphabetical	Sentence (nonalphabetical)	+ The child's hands and feet slowly grew very numb.	The dancer moved her hands and feet gracefully, commanding the stage.
feet and hands	-0.3822570	0.4219807	unrelated	Sentence (alphabetical)	+ The child's feet and hands slowly grew very numb.	The crisp autumn air was filled with the scent of pine and fallen leaves.
feet and hands	-0.3822570	0.4219807	unrelated	Sentence (nonalphabetical)	+ The child's hands and feet slowly grew very numb.	The crisp autumn air was filled with the scent of pine and fallen leaves.
gas and oil	-0.4145522	0.4149414	alphabetical	Sentence (alphabetical)	+ Sam didn't know the difference between gas and oil so she ruined her car.	The economy in this region is heavily dependent on gas and oil production.

gas and oil	-0.4145522	0.4149414	alphabetical	Sentence (nonalphabetical)	+ Sam didn't know the difference between oil and gas so she ruined her car.	The economy in this region is heavily dependent on gas and oil production.
gas and oil	-0.4145522	0.4149414	nonalphabetical	Sentence (alphabetical)	+ Sam didn't know the difference between gas and oil so she ruined her car.	The economy in this region is heavily dependent on oil and gas production.
gas and oil	-0.4145522	0.4149414	nonalphabetical	Sentence (nonalphabetical)	+ Sam didn't know the difference between oil and gas so she ruined her car.	The economy in this region is heavily dependent on oil and gas production.
gas and oil	-0.4145522	0.4149414	unrelated	Sentence (alphabetical)	+ Sam didn't know the difference between gas and oil so she ruined her car.	He sat by the campfire, warming his hands as the stars sparkled above.
gas and oil	-0.4145522	0.4149414	unrelated	Sentence (nonalphabetical)	+ Sam didn't know the difference between oil and gas so she ruined her car.	He sat by the campfire, warming his hands as the stars sparkled above.
death and life	-0.4380721	0.1047131	alphabetical	Sentence (alphabetical)	+ It is hard to tell the difference between death and life when you are in purgatory.	In many cultures, death and life are seen as intertwined parts of a greater cycle.
death and life	-0.4380721	0.1047131	alphabetical	Sentence (nonalphabetical)	+ It is hard to tell the difference between life and death when you are in purgatory.	In many cultures, death and life are seen as intertwined parts of a greater cycle.
death and life	-0.4380721	0.1047131	nonalphabetical	Sentence (alphabetical)	+ It is hard to tell the difference between death and life when you are in purgatory.	In many cultures, life and death are seen as intertwined parts of a greater cycle.
death and life	-0.4380721	0.1047131	nonalphabetical	Sentence (nonalphabetical)	+ It is hard to tell the difference between life and death when you are in purgatory.	In many cultures, life and death are seen as intertwined parts of a greater cycle.
death and life	-0.4380721	0.1047131	unrelated	Sentence (alphabetical)	+ It is hard to tell the difference between death and life when you are in purgatory.	The child's laughter echoed through the park as he chased after a butterfly.
death and life	-0.4380721	0.1047131	unrelated	Sentence (nonalphabetical)	+ It is hard to tell the difference between life and death when you are in purgatory.	The child's laughter echoed through the park as he chased after a butterfly.
boys and girls	0.3825196	0.6258780	alphabetical	Sentence (alphabetical)	+ The teacher separated the boys and girls into two small groups.	Boys and girls eagerly gathered around the storyteller for an afternoon of tales.
boys and girls	0.3825196	0.6258780	alphabetical	Sentence (nonalphabetical)	+ The teacher separated the girls and boys into two small groups.	Boys and girls eagerly gathered around the storyteller for an afternoon of tales.
boys and girls	0.3825196	0.6258780	nonalphabetical	Sentence (alphabetical)	+ The teacher separated the boys and girls into two small groups.	Girls and boys eagerly gathered around the storyteller for an afternoon of tales.
boys and girls	0.3825196	0.6258780	nonalphabetical	Sentence (nonalphabetical)	+ The teacher separated the girls and boys into two small groups.	Girls and boys eagerly gathered around the storyteller for an afternoon of tales.
boys and girls	0.3825196	0.6258780	unrelated	Sentence (alphabetical)	+ The teacher separated the boys and girls into two small groups.	The mountain trail was steep, but the view from the top made every step worth it.
boys and girls	0.3825196	0.6258780	unrelated	Sentence (nonalphabetical)	+ The teacher separated the girls and boys into two small groups.	The mountain trail was steep, but the view from the top made every step worth it.
cause and effect	0.4893921	0.7803896	alphabetical	Sentence (alphabetical)	+ Ryan was uncertain about the cause and effect of inflation, so he did some research.	The gathering was filled with laughter from brothers and sisters catching up after a long time apart.
cause and effect	0.4893921	0.7803896	alphabetical	Sentence (nonalphabetical)	+ Ryan was uncertain about the effect and cause of inflation, so he did some research.	The gathering was filled with laughter from brothers and sisters catching up after a long time apart.
cause and effect	0.4893921	0.7803896	nonalphabetical	Sentence (alphabetical)	+ Ryan was uncertain about the cause and effect of inflation, so he did some research.	The gathering was filled with laughter from sisters and brothers catching up after a long time apart.
cause and effect	0.4893921	0.7803896	nonalphabetical	Sentence (nonalphabetical)	+ Ryan was uncertain about the effect and cause of inflation, so he did some research.	The gathering was filled with laughter from sisters and brothers catching up after a long time apart.
cause and effect	0.4893921	0.7803896	unrelated	Sentence (alphabetical)	+ Ryan was uncertain about the cause and effect of inflation, so he did some research.	She carefully wrapped the gift, tying a red ribbon into a perfect bow.
cause and effect	0.4893921	0.7803896	unrelated	Sentence (nonalphabetical)	+ Ryan was uncertain about the effect and cause of inflation, so he did some research.	She carefully wrapped the gift, tying a red ribbon into a perfect bow.
pepper and salt	-0.4392495	0.2688839	alphabetical	Sentence (alphabetical)	+ The food is in need of pepper and salt because it's rather bland.	She added just a pinch of pepper and salt to bring out the flavors of the dish.
pepper and salt	-0.4392495	0.2688839	alphabetical	Sentence (nonalphabetical)	+ The food is in need of salt and pepper because it's rather bland.	She added just a pinch of pepper and salt to bring out the flavors of the dish.
pepper and salt	-0.4392495	0.2688839	nonalphabetical	Sentence (alphabetical)	+ The food is in need of pepper and salt because it's rather bland.	She added just a pinch of salt and pepper to bring out the flavors of the dish.
pepper and salt	-0.4392495	0.2688839	nonalphabetical	Sentence (nonalphabetical)	+ The food is in need of salt and pepper because it's rather bland.	She added just a pinch of salt and pepper to bring out the flavors of the dish.
pepper and salt	-0.4392495	0.2688839	unrelated	Sentence (alphabetical)	+ The food is in need of pepper and salt because it's rather bland.	The dog barked at the mailman every day, as if it were his sworn duty.
pepper and salt	-0.4392495	0.2688839	unrelated	Sentence (nonalphabetical)	+ The food is in need of salt and pepper because it's rather bland.	The dog barked at the mailman every day, as if it were his sworn duty.
female and male	-0.4263521	0.3493327	alphabetical	Sentence (alphabetical)	+ The dog breeder said the female and male puppies are coming today.	The study found no significant differences in learning styles between female and male students.
female and male	-0.4263521	0.3493327	alphabetical	Sentence (nonalphabetical)	+ The dog breeder said the male and female puppies were coming today.	The study found no significant differences in learning styles between female and male students.

female and male	-0.4263521	0.3493327	nonalphabetical	Sentence (alphabetical)	+ The dog breeder said the female and male puppies are coming today.	The study found no significant differences in learning styles between male and female students.
female and male	-0.4263521	0.3493327	nonalphabetical	Sentence (nonalphabetical)	+ The dog breeder said the male and female puppies were coming today.	The study found no significant differences in learning styles between male and female students.
female and male	-0.4263521	0.3493327	unrelated	Sentence (alphabetical)	+ The dog breeder said the female and male puppies are coming today.	She wrote down her goals in a new journal, determined to make this year different.
female and male	-0.4263521	0.3493327	unrelated	Sentence (nonalphabetical)	+ The dog breeder said the male and female puppies were coming today.	She wrote down her goals in a new journal, determined to make this year different.
brothers and sisters	0.4142403	0.6388390	alphabetical	Sentence (alphabetical)	+ Andrew shared with his brothers and sisters, so he was excited to have a roomate.	I always love seeing my brothers and sisters when I go home for the holidays.
brothers and sisters	0.4142403	0.6388390	alphabetical	Sentence (nonalphabetical)	+ Andrew shared with his sisters and brothers, so he was excited to have a roomate.	I always love seeing my brothers and sisters when I go home for the holidays.
brothers and sisters	0.4142403	0.6388390	nonalphabetical	Sentence (alphabetical)	+ Andrew shared with his brothers and sisters, so he was excited to have a roomate.	I always love seeing my sisters and brothers when I go home for the holidays.
brothers and sisters	0.4142403	0.6388390	nonalphabetical	Sentence (nonalphabetical)	+ Andrew shared with his sisters and brothers, so he was excited to have a roomate.	I always love seeing my sisters and brothers when I go home for the holidays.
brothers and sisters	0.4142403	0.6388390	unrelated	Sentence (alphabetical)	+ Andrew shared with his brothers and sisters, so he was excited to have a roomate.	They exchanged a knowing glance, each understanding the other's unspoken thoughts.
brothers and sisters	0.4142403	0.6388390	unrelated	Sentence (nonalphabetical)	+ Andrew shared with his sisters and brothers, so he was excited to have a roomate.	They exchanged a knowing glance, each understanding the other's unspoken thoughts.
fall and rise	-0.4700519	0.4320348	alphabetical	Sentence (alphabetical)	+ I've gotten particularly ill due to the fall and rise of the big waves.	The documentary charts the fall and rise of a once-beloved artist.
fall and rise	-0.4700519	0.4320348	alphabetical	Sentence (nonalphabetical)	+ I've gotten particularly ill due to the rise and fall of the big waves.	The documentary charts the fall and rise of a once-beloved artist.
fall and rise	-0.4700519	0.4320348	nonalphabetical	Sentence (alphabetical)	+ I've gotten particularly ill due to the fall and rise of the big waves.	The documentary charts the rise and fall of a once-beloved artist.
fall and rise	-0.4700519	0.4320348	nonalphabetical	Sentence (nonalphabetical)	+ I've gotten particularly ill due to the rise and fall of the big waves.	The documentary charts the rise and fall of a once-beloved artist.
fall and rise	-0.4700519	0.4320348	unrelated	Sentence (alphabetical)	+ I've gotten particularly ill due to the fall and rise of the big waves.	She gazed out at the ocean, mesmerized by the endless waves crashing against the shore.
fall and rise	-0.4700519	0.4320348	unrelated	Sentence (nonalphabetical)	+ I've gotten particularly ill due to the rise and fall of the big waves.	She gazed out at the ocean, mesmerized by the endless waves crashing against the shore.
feelings and thoughts	-0.3486352	0.4183383	alphabetical	Sentence (alphabetical)	+ When Pat gets frustrated, her feelings and thoughts get muddled quite quickly.	Poetry often tries to capture the subtle interplay of feelings and thoughts.
feelings and thoughts	-0.3486352	0.4183383	alphabetical	Sentence (nonalphabetical)	+ When Pat gets frustrated, her thoughts and feelings get muddled quite quickly.	Poetry often tries to capture the subtle interplay of feelings and thoughts.
feelings and thoughts	-0.3486352	0.4183383	nonalphabetical	Sentence (alphabetical)	+ When Pat gets frustrated, her feelings and thoughts get muddled quite quickly.	Poetry often tries to capture the subtle interplay of thoughts and feelings.
feelings and thoughts	-0.3486352	0.4183383	nonalphabetical	Sentence (nonalphabetical)	+ When Pat gets frustrated, her thoughts and feelings get muddled quite quickly.	Poetry often tries to capture the subtle interplay of thoughts and feelings.
feelings and thoughts	-0.3486352	0.4183383	unrelated	Sentence (alphabetical)	+ When Pat gets frustrated, her feelings and thoughts get muddled quite quickly.	He flipped through the album, each photograph bringing back a flood of memories.
feelings and thoughts	-0.3486352	0.4183383	unrelated	Sentence (nonalphabetical)	+ When Pat gets frustrated, her thoughts and feelings get muddled quite quickly.	He flipped through the album, each photograph bringing back a flood of memories.
days and nights	0.4144469	0.6530894	alphabetical	Sentence (alphabetical)	+ Finn spent many days and nights working on writing his novel.	The desert's harshness is evident in the extreme days and nights.
days and nights	0.4144469	0.6530894	alphabetical	Sentence (nonalphabetical)	+ Finn spent many nights and days working on writing his novel.	The desert's harshness is evident in the extreme days and nights.
days and nights	0.4144469	0.6530894	nonalphabetical	Sentence (alphabetical)	+ Finn spent many days and nights working on writing his novel.	The desert's harshness is evident in the extreme nights and days.
days and nights	0.4144469	0.6530894	nonalphabetical	Sentence (nonalphabetical)	+ Finn spent many nights and days working on writing his novel.	The desert's harshness is evident in the extreme nights and days.
days and nights	0.4144469	0.6530894	unrelated	Sentence (alphabetical)	+ Finn spent many days and nights working on writing his novel.	The crowded marketplace buzzed with the sounds of bargaining and laughter.
days and nights	0.4144469	0.6530894	unrelated	Sentence (nonalphabetical)	+ Finn spent many nights and days working on writing his novel.	The crowded marketplace buzzed with the sounds of bargaining and laughter.