Journal of Memory and Language 146 (2026) 104708



Contents lists available at ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml



Do people structure words and sentences using shared mechanisms?

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ARTICLE INFO

Keywords:
Structural priming
Attachment ambiguity
Domain generality

ABSTRACT

The same sequence of linguistic units can be structured differently: Relative clauses in sentences such as "I met the students of the teacher who played the violin" can either have a high attachment (HA; i.e., the students played the violin) or low attachment reading (LA; i.e., the teacher played the violin). Similarly, morphological attachment in noun phrases such as "social psychologist" can have either an HA (i.e., someone who studies social psychology; [[social psycholog(y)][ist]]) or LA reading (i.e., a psychologist who is social; [[social][[psycholog(y)][ist]]]). Thus, abstractly at least, sentences and words have analogous internal hierarchical structures. Using a structural priming paradigm, we investigated in three experiments whether shared mechanisms process the internal structures of both sentences and words, despite the difference in grain size. Overall, we only observed priming effects when the primes and targets were of the same grain size: Participants produced more HA sentences or rated the HA readings of ambiguous sentences as more probable following HA sentence primes (compared to following LA sentence primes), while the attachment structure of morphological primes did not affect subsequent sentence production and comprehension. Participants also rated the HA readings of ambiguous noun phrases as more probable following HA morphological primes (compared to following LA morphological primes), while the attachment of sentence primes did not affect subsequent morphological comprehension. We suggest that at least as reflected by structural priming, structural operations are not shared across morphological and syntactic levels.

Introduction

Producing language involves generating temporally or spatially linear sequences of sounds or symbols, which are the products of piecing together smaller units to form bigger units; from morphemes to words, from words to phrases, and from phrases to sentences. These linguistic units are organized in a hierarchical manner, as the functions and meanings of the units are determined by the process of integrating units that are not necessarily adjacent to one another. As such, the same linear sequence of linguistic units can be structured in different ways, and the message or interpretation could differ depending on the specific structure one commits to. For example, in sentences such as "I met the students of the teacher who played the violin", the relative clause "who played the violin" can either have a high attachment (HA) configuration, which means "the students" played the violin, or a low attachment (LA) configuration, which means "the teacher" played the violin. Similarly, in noun phrases such as "social psychologist", the morpheme "-ist" can either attach high to "social psycholog(y)" to mean someone who studies the discipline of social psychology, or attach low to "psycholog(y)" only to mean someone who studies psychology and enjoys the companionship of others. Despite the difference in the grain size of the linguistic units involved, these examples illustrate that words and sentences are at least abstractly similar in their internal structures, in that processing words and sentences both require combining hierarchically organized units. That leads to the question: Are the cognitive mechanisms that process the internal structures of words and sentences shared? Here we first introduce paradigms in structural priming, which have been commonly used to test whether two superficially distinct forms of structures share the same underlying representation or operation. Then, we review previous work on cross-domain and linguistic priming.

Speakers can often choose between multiple structures to convey a similar message, but studies have shown that they are more likely to repeat a sentence structure that they have recently been exposed to (say, in the preceding sentence) than to produce an alternative structure that conveys a similar meaning, even if the priming and the primed material are not conceptually related. This phenomenon of abstract structure

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https://doi.org/10.1016/j.jml.2025.104708
Received 22 March 2023; Received in revised form 18 October 2025; Accepted 20 October 2025
Available online 25 October 2025
0749-596X/Published by Elsevier Inc.

reuse is one form of *structural priming*. For example, in a picture description task, Bock (1986) found that after participants heard and repeated out loud a passive voice prime sentence (e.g., "The referee was punched by one of the fans"), as opposed to an active voice prime sentence (e.g., "One of the fans punched the referee"), they were more likely to subsequently describe an unrelated target picture in passive voice (e.g., "The church is being struck by lightning"). Similar patterns were also found for other structures, such as between producing a prepositional dative (e.g., "The rock star sold some cocaine to the undercover agent") or a double object dative sentence (e.g., "A rock star sold the undercover agent some cocaine"; see Bock, 1986, 1989, and Bock & Loebell, 1990); and between completing the relative clause sentence fragment "The pensioner railed about the author of the fliers that…" with an HA (describing the author) versus LA continuation (describing the fliers; Scheepers, 2003).

Structural priming has also been observed in comprehension (see Tooley & Traxler, 2010 for a review). For example, Pickering et al. (2013) used a sentence-picture matching task to observe priming in the interpretation of sentences with ambiguous prepositional phrase attachment such as "The waitress is prodding the clown with the umbrella," with either the HA interpretation (i.e., the waitress is using the umbrella to prod) or the LA interpretation (i.e., the clown has an umbrella). They manipulated the attachment interpretation of prime sentences by asking participants to select a picture that matched a prime sentence, with only one picture matching either the HA or LA interpretation of the prime sentence. In the target items, participants performed the same task again, except that they picked between a picture depicting the HA interpretation and another depicting the LA interpretation instead. Results showed that after reading a sentence with a particular attachment interpretation, comprehenders were more likely to interpret the following sentence the same way.

Patterns of structural priming have been replicated regardless of whether participants were exposed to the primes through reading and repeating (Bock, 1986), reading and picture-matching (Pickering et al., 2013), writing (Pickering & Branigan, 1998), typing (Corley & Scheepers, 2002), or listening to another interlocutor in dialogue (Branigan et al., 2000). Indeed, Tooley's (2023) review contrasting structural priming effects in production and comprehension concluded that abstract structural priming occurs in both modalities. Differences that are sometimes observed between production and comprehension studies likely reflect differences in dependent variables and tasks, rather than speakers and comprehenders engaging different modality-specific cognitive mechanisms. Priming is also observed between modalities, that is, from comprehension to production (Bock et al., 2007) and from production to comprehension (Ferreira et al., 2012). That is, structuring operations in language appear to be modality-independent. Generally, the aforementioned studies suggest that structural priming occurs because the representation of the abstract sentence structure in use remains accessible for some time, making that template more likely to be reused compared to its alternatives (see Pickering & Ferreira, 2008 for a review on structural priming and its implications for models of language processing). Thus, when structural priming occurs between two linguistic units that are seemingly different on the surface, the units are argued to likely have a shared underlying structural representation in processing.

Even though structural priming has been found with various linguistic structures, some argue that priming effects on active/passive voice and dative constructions may not be purely structural because the lexical entries of verbs include information about argument structure of the sentence (e.g., Ziegler et al., 2019). On the contrary, because relative clauses are modifiers that are not commonly viewed as part of the core argument structure of a lexical item, they are likely not encoded in the lexical entries of the nouns that they modify and thus in some ways provide a more purely structural test case for priming (e.g., Desmet & Declercq, 2006, Scheepers, 2003). However, it is important to note that relative clause attachment priming is qualitatively different from other forms of structural priming. In particular, the two attachment alternatives convey different propositional meanings of "who did what to whom" (compared to standard alternations such as transitives and datives, where the message is comparable between the two alternative structures). Because the choice of attachment structure is conflated with the choice of propositional meaning, Pickering and Ferreira (2008) suggested that relative clause attachment priming is at least in part message level or comprehension priming. From a production perspective, attachment manipulations may affect speakers' subsequent choice of meaning because the typical sentence continuation (target production) task does not require speakers to commit to expressing one meaning versus the other, making message priming possible. From a comprehension perspective, attachment manipulations may prime the speakers to comprehend the target fragment as HA or LA before continuing with their production, suggesting that the source of any priming effect is a comprehension process. Nevertheless, relative clause attachment priming has been widely used as a test for shared structuring mechanisms in linguistic and non-linguistic domains alike.

Within the language domain, relative clause attachment priming has been used to study whether bilinguals have shared structural representations for the two languages that they speak. For example, Desmet and Declercq (2006) demonstrated cross-linguistic relative clause attachment priming from Dutch to English in Dutch-English bilinguals. Participants first completed a sentence fragment such as "Gabriel scratched on the cover of the magazine that…" in Dutch, where "that" was manipulated to induce an HA or LA attachment with grammatical gender features agreeing with either "the cover" or "the magazine," respectively. Then, participants completed another fragment in English that did not contain attachment-biasing grammatical features (e.g., "The farmer fed the calves of the cow that…"). The results replicated the structural priming effect: Participants were more likely to produce HA continuations in English following HA Dutch primes, compared to following LA Dutch primes. Similarly, Hartsuiker et al. (2016) reported cross-linguistic priming in Dutch-French-English trilinguals, regardless of whether priming was between the first and second language or two different second languages. The authors took cross-linguistic relative clause attachment priming as evidence that bilinguals may have a single abstract representation for each of the relative clause attachment structures that is shared between the languages they speak (see Van Gompel & Arai, 2018 for a review on structural priming in bilinguals).

Priming effects of attachment height in relative clauses can be explained by two different accounts of what information is mentally represented. Scheepers (2003) suggested that priming results from the specific order of applying the same set of phrase-structure rules. This account is supported by the basic attachment priming effects that were described above. Alternatively, Desmet and Declercq (2006) proposed a much more general account that it is the abstract attachment height and location that is being represented independently of phrase-structure rules. In a sentence completion task, Loncke et al. (2011) found that relative clause attachment (identical structure with the target, e.g., "The tables of the restaurant that…", with "that" grammatically agreeing with "the tables" or "the restaurant") and prepositional phrase attachment (dissimilar structure with the target, e.g., "The tables of the restaurant with their/with its…") both primed subsequent relative clause attachment. That is, priming can occur both within the same structure and between two different structures, which supports the more general account that structural priming of attachment occurs due to the activation of a representation of the abstract hierarchical configuration (instead of the activation of sequences of phrase-structure rules).

Outside of language, humans frequently interact with hierarchical structures in other domains of cognition, which raises the question of whether structuring mechanisms of abstract structures are domain-general – that is, extend to representational domains beyond language. For example, parentheses are used in arithmetic to denote the order and scope of operations, and the resulting configurations of equations sometimes resemble the structure of relative clause sentences. Scheepers

et al. (2011) noted these structural similarities and tested whether priming occurs across arithmetic and language. They found that participants were more likely to produce an HA sentence continuation after successfully solving an equation with a structure analogous to an HA relative clause (e.g., 80 − (9 + 1) × 5) than after solving a baseline equation without hierarchical structure (e.g., 5 + 15). Similarly, participants were more likely to produce a LA sentence continuation after solving an equation analogous to a LA relative clause (e.g., 80–9 + 1 × 5) than after the baseline condition. The observation of cross-domain structural priming suggests that hierarchical structural information (such as the global configuration or the shape of the structure) may be represented at a very high level of abstraction such that it may be shared across domains.

In a later conceptual replication of the math-to-language priming effect (Scheepers & Sturt, 2014), it was shown that the effect is bidirectional (i.e., language-to-math priming also occurs) and extends beyond the sentence level to adjective-noun-noun compounds. Arithmetic equations and adjective-noun-noun compounds are similar in that they can both be organized as left- (i.e., (A B) C structure) or right-branching (i.e., A (B C) structure), such as "5 × 2 + 7" versus "5 + 2 × 7" in math, and "organic coffee dealer" (meaning "a dealer of organic coffee" rather than "a coffee dealer who is organic") versus "bankrupt coffee dealer" (meaning "a coffee dealer who is bankrupt" rather than "a dealer of bankrupt coffee") in adjective-noun-noun compounds. In a series of experiments where participants solved math equations and gave sensibility ratings (on a scale of 1 "makes no sense" to 5 "makes perfect sense") for the linguistic compounds, it was found that sensibility ratings for linguistic items were higher after successfully solving an equation of a congruent branching structure, compared to an incongruent one, replicating the math-to-language priming effect. Moreover, in a sample of participants who were predetermined to be relatively less adept in math, arithmetic equations were more likely to be successfully solved after giving sensibility ratings for linguistic components of a congruent branching structure, compared to an incongruent one, demonstrating a language-to-math priming effect. Once again, these results corroborate the claim that structural representation may be domain-general.

Note, however, that both Scheepers et al. (2011) and Scheepers and Sturt (2014) pointed out that math priming effects are sensitive to many extraneous factors, such as whether the instructions of the task explicitly remind participants of the rules of arithmetic order of operations, whether there are redundant parentheses in the math equations, and the participants' baseline math abilities. Nevertheless, Van de Cavey and Hartsuiker (2016) further supported the cross-domain shared structural representation account by providing evidence for both within- and cross-domain priming. Specifically, attachment configurations in prime items constructed with musical sequences, math, structured descriptions of events, and relative clause sentences affected subsequent attachment preferences in relative clause production. Additionally, the magnitude of priming effects did not differ by whether the prime was cross-domain or within-domain. Note, however, that when the targets were structured descriptions of events, there was a slight advantage of within-domain priming: attachment preferences in subsequent event descriptions were influenced most strongly by attachment configurations in event description primes, marginally less by relative clause primes, and significantly less by music and math primes.

If structuring mechanisms are shared across cognitive domains, as suggested by the ubiquitous cross-domain priming effects found across different tasks and linguistic structures, it seems reasonable to assume that the mechanisms may also be shared within the language domain across units of different grain sizes (i.e., across words and sentences). There is suggestive evidence from priming between math and language that this assumption may be true. Recall that Scheepers et al. (2011) found that math primed relative clause sentences, whereas Scheepers and Sturt (2014) found bidirectional priming between math and compounds of words. When combined together, these two studies suggest that relative clause sentences and compounds of words may prime each other, despite the difference in grain size. The current work aims to test that exact prediction and confirm whether words and sentences indeed have shared structuring mechanisms.

Experiment 1 tested whether attachment in relative clause sentence production and free recall of noun phrases affected subsequent relative clause sentence production; Experiment 2 tested whether attachment in sentence production and noun phrase interpretation affected subsequent noun phrase interpretation; and lastly, Experiment 3 simultaneously tested whether attachment in sentence and noun phrase interpretation affected subsequent sentence and noun phrase interpretation. If structuring mechanisms across different linguistic levels are shared, we should expect preferences in relative clause attachment in sentences and morphological attachment in words to affect subsequent attachment preferences both within- and across-grain size. Conversely, if structuring mechanisms are not shared, we should expect sentence attachment to only affect subsequent sentence attachment but not morphological attachment, and vice versa.

Experiment 1

Data availability

The data, analysis scripts, and pre-registration reports can be found at https://osf.io/jrmkw/.

Method

Participants

Sixty undergraduates from the University of California San Diego participated in the experiment in exchange for course credit. Twelve participants were excluded from our analyses because they either did not produce more than 50 % usable data (exclusion criteria explained below in Coding and Data Analysis) or did not complete the experiment due to technical issues. All 48 remaining participants indicated that they were native English speakers.

Materials

The experiment was hosted on Qualtrics. We used a within-subjects 2 (Prime Attachment: High or Low) × 2 (Prime Type: Sentence or Morphological) design. Each trial contained one prime and one target. That is, for each trial, participants either completed a sentence fragment prime (Sentence condition) or memorized a morphological prime (Morphological condition), which either has a predominantly high (HA) or low attachment (LA) meaning, before completing the target sentence continuation task (see Procedure section below). Both the prime and target sentence fragments were adopted from Desmet and Declercq (2006) and Scheepers et al. (2011), whereas the morphological primes were designed for the current work. There were 24 sentence primes and 24 morphological primes, with an equal split of HA and LA for each prime type. There were 48 target items in total (i.e., each participant completed 48 critical trials in this experiment). Participants were randomly assigned to one of two experimental lists, which counterbalanced whether a given target item was preceded by an HA or LA prime.

The sentence primes were sentence fragments with agreement features that coerced the production of a high or low attachment continuation, such as "The firemen saved the residents of the penthouse *who were*… (HA; coercing a continuation about the residents)/*that was*… (LA; coercing a continuation about the penthouse)". For morphological primes, we constructed noun phrases of professions that either had predominantly high or low attachment meanings. For example, "primate researcher" was considered an HA item, with the morpheme "-er" attaching to a higher and larger unit of "primate research" to mean someone who studies primates (i.e., [[primate research][er]]) rather than a primate that conducts academic studies (i.e., [[primate]

[[research][er]]]); whereas "diligent researcher" was considered an LA item, with "-er" attaching low to "research" to mean a hardworking person who conducts academic studies (i.e., [[diligent][[research][er]]]) rather than someone who studies a discipline called "diligent research" (i.e., [[diligent research][er]]).

Similar to the sentence primes, the target items were also sentence fragments, except that they did not contain agreement features that biased attachment preferences. For example, in the fragment "the florist befriended the servant of the princesses who…", participants could freely choose to describe the servant (HA) or the princesses (LA).

In addition to the critical trials, participants also completed 24 filler trials, which were interleaved with the target trials in a pseudorandomized order such that participants did not complete more than two trials of the same type in a row. The filler primes were mathematical primes adapted from the original study that reported the math priming effect (Scheepers et al., 2011), with half of them being arithmetic equations with HA structures (e.g., "31 + (8 – 5) × 2") and the other half with LA structures (e.g., "31 + 8 – 5 × 2"). Similar to critical trials, the target items were sentence fragments that allowed participants to freely produce a high or low attachment continuation. An analysis of the filler items revealed that we failed to replicate the math priming effect. That is, participants were about equally likely to produce a HA continuation regardless of whether they successfully solved an HA or LA arithmetic problem beforehand (44.1 % vs. 43.3 %; $\beta = 0.002$, $SE = 0.16$, $z = 0.01$, $p = .99$). We performed a follow-up, Bayesian analysis to distinguish a true null effect and inconclusive evidence, and Bayes Factor comparisons provide strong evidence for a null model with no effect of priming ($\beta = -0.03$, 95 % CI = [-0.33, 0.27], $BF_{10} = 0.079$). Given the main goal of the current work to establish whether there are shared cognitive mechanisms between linguistic units of different grain size rather than across domains, we did not continue to include the mathematical fillers in later experiments and focus our discussion below on any potential linguistic priming effects.

The full list of prime and target materials for Experiment 1 can be found in Appendix A.

Procedure

Participants completed the experiment hosted on Qualtrics in the laboratory under the supervision of an experimenter. All responses were produced by typing.

Each trial consisted of a prime and a target task. The prime was either a sentence or a morphological prime, which was manipulated to have either a high (HA) or low (LA) attachment structural organization. Participants were given instructions to perform a sentence continuation task and a noun phrase free recall task, but they were not informed of the prime-target manipulation. For sentence continuation, participants were instructed to type a response that formed a complete sentence whenever they were presented with a sentence fragment. For free recall, participants were told to expect to see a noun phrase displayed on the screen for three seconds and to memorize the given noun phrase in preparation for free recall at a later time. Free recall for each morphological prime was always prompted immediately after the associated target item. In other words, when the participant completed a trial with a sentence prime, they first completed a sentence with attachment-biasing agreement features, then another sentence without such features. If the participant completed a trial with a morphological prime, they first saw a noun phrase and attempted to keep it in their working memory while completing a sentence without attachment-biasing agreement features, then recalled the noun phrase afterwards.

Coding and analyses

Every prime response that was incompatible with our intended prime attachment manipulation (i.e., when participants ignored the sentence agreement features or inaccurately recalled the memory items) was deemed invalid and left out of our analyses. Additionally, target responses in which it was unclear whether the relative clause modified the high or low attachment noun phrase were also excluded. There were 1,782 (out of 2,304; 77 %) analyzable trials in total. Of the excluded trials, 262 were sentence prime items that did not elicit the intended attachment (i.e., participants creating sentences that violated agreement features) and 260 were morphological prime items that were misremembered. Valid target responses were coded in terms of whether the freely produced relative clause attached high (HA) or low (LA).

We built a generalized linear mixed effects model with the dependent variable of whether the target response was HA (1) or LA (0), in order to analyze the likelihood of HA sentence continuation as a function of Prime Type (sentence or morphological), Prime Attachment (HA or LA), and their interaction. Fixed effects were sum-coded. Although we attempted to use the maximal random effects structure for both models, we removed all random slopes due to convergence issues. The model included random intercepts for participants and items.

Post-hoc Bayesian analyses

Frequentist analyses can only reject a null hypothesis, so we performed post-hoc Bayesian analyses to adjudicate whether observed null results from frequentist analyses reflect support for the null hypothesis or whether the results are simply inconclusive. These analyses were not pre-registered. Using the *brms* package in R (Bürkner, 2019), we fit generalized linear mixed effects models with the same specifications as the frequentist models. We assumed a Bernoulli distribution with a logit link function due to the binary nature of the data. We used default priors for all random effects and variance estimates (half-student *t*-distributions with 3 degrees of freedom). All priors are in log-odds terms. We did not use default priors for coefficients of fixed effects, as these default priors are uniform (and, therefore, improper), and using them can lead to inconsistent calculations. Coefficient estimates for fixed effects were given a normal prior with a mean of 0 and a standard deviation of 2. This prior choice avoids flat, improper priors but is wide enough to avoid making stringent assumptions. Each Bayesian model had four Markov Chain Monte Carlo (MCMC) chains of 10,000 iterations total, 2,000 of which were for warm-up. This resulted in 32,000 post-warm up samples per model. Divergent transitions during sampling can lead to inaccurate posterior estimates, so when we encountered divergent transitions, we increased "adapt delta" from the default value of 0.85. Higher values of this parameter slow down the sampler but ensure more accurate transitions. All R-hat values were equal to 1.00 after sampling, indicating no convergence issues.

For critical (sentence and morphological priming) trials, we fit five nested models for our main analysis: a full model with Prime Type, Prime Attachment, and a Prime Type × Prime Attachment interaction; a model with both main effects but no interaction term; a model with only Prime Type as a fixed effect; a model with only Prime Attachment as a fixed effect; and an intercept-only model (i.e., a model without fixed effects). We fit four models for the follow-up planned comparisons. Within each prime type, we fit models with and without prime attachment as a fixed effect. We compared nested models using *brms* functions to produce Bayes Factors indicating relative support for one model over the other. We generally used guidelines from Kass and Raftery (1995) when interpreting strength of evidence given by Bayes Factors but these analyses (and, therefore, these inference criteria) were not pre-registered. Generally, Bayes Factors less than 1 indicate relative support for the model with fewer terms, and Bayes Factors greater than 1 indicate relative support for the model with more terms. We reported the coefficient estimate of the term, the 95 % credible interval of the coefficient estimate, and the Bayes Factor.

Results and discussion

Fig. 1 shows the average proportion of HA responses following HA or LA sentence or morphological primes. On average, participants were numerically more likely to produce a HA sentence following a HA prime, compared to a LA prime (the main effect of Prime Attachment was marginally significant; $\beta = -0.20$, $SE = 0.11$, $z = -1.86$, $p = .06$). We

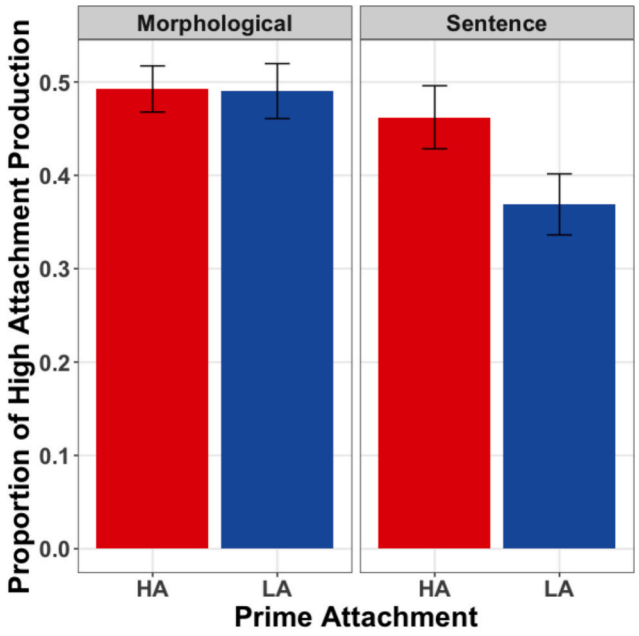


Fig. 1. Proportion of high attachment sentence continuations following high- or low-attachment morphological or sentence primes, color-coded by prime attachment and separated into two panels by prime type. Error bars represent standard errors.

also observed a marginal Prime Type × Prime Attachment interaction ($\beta = -0.38$, $SE = 0.21$, $z = -1.76$, $p = .08$). Participants were no more likely to produce HA sentences following HA morphological primes ($M = 49.2$ %, $SE = 2.47$ %), compared to following LA morphological primes ($M = 49$ %, $SE = 2.94$ %); the pairwise comparison was not significant ($z = 0.07$, $p = .94$). However, participants were 9.3 % more likely to produce HA sentences following HA sentence primes ($M = 46.2$ %, $SE = 3.38$ %), compared to following LA sentence primes ($M = 36.9$ %, $SE = 3.27$ %), and this pairwise comparison was significant ($z = 2.56$, $p = .01$).

We performed three Bayes Factor comparisons between nested models. First, to evaluate the Prime Type × Prime Attachment interaction, we compared the full model to a reduced model with Prime Type and Prime Attachment as fixed effects but no interaction. The Bayes Factor obtained is generally considered to indicate inconclusive evidence ($\beta = -0.37$, 95 % CI = [-0.80, 0.05], $BF_{10} = 0.489$). Follow-up planned comparisons show evidence against an effect of Prime Attachment with morphological primes ($\beta = 0.02$, CI = [-0.49, 0.50], $BF_{10} = 0.074$). There was equivocal evidence for a main effect of Prime Attachment with sentence primes ($\beta = -0.42$, CI = [-0.72, −0.12], $BF_{10} = 2.96$), but the model estimates are numerically consistent with the frequentist statistics. To test for main effects, we compared a model with the term of interest to the intercept-only model. We found evidence against main effects of Prime Type ($\beta = -0.34$, CI = [-0.89, 0.20], $BF_{10} = 0.300$) and Prime Attachment ($\beta = -0.20$, CI = [-0.41, 0.01], $BF_{10} = 0.310$).

In sum, our results from Experiment 1 provide suggestive evidence that only sentence (but not morphological) attachment preference affected later sentence production. The marginal interaction is consistent with the possibility that the structuring mechanisms between the two levels may not be shared. However, the lack of morphological effect on later sentence production may be attributed to one limitation of the design: The free recall task did not require the participants to think about the possible meanings of the morphological primes. If the hierarchical structures of morphemes that give rise to different meanings of noun phrases were not activated by the free recall task, the absence of priming effects in the morphological conditions may reflect this limitation, rather than a distinct structuring mechanism for words. To further test the robustness and directionality of the priming effects (or the lack thereof), we changed how the morphological primes were presented and switched the target task to a morphological task in Experiment 2.

Experiment 2

Method

Participants

Two hundred and fifty-two undergraduates from the University of California San Diego participated in exchange for course credit. All participants indicated that they were native English speakers. Experiment 2 contained many fewer trials than did Experiment 1 (only eight items), so a power analysis was conducted using data from a pilot experiment to determine the target sample size. The analysis estimated that 250 participants would be sufficient to achieve 80 % power in this experiment. All participants produced more than 50 % valid data for analysis (see Coding and Analyses for criteria) and thus no one was excluded.

Materials

Similar to Experiment 1, we used a within-subjects 2 (Prime Attachment: High or Low) × 2 (Prime Type: Sentence or Morphological) design, with each trial containing a prime and target pair. The sentence primes were sentence fragments with agreement features that coerced either a high (HA) or low attachment (LA) continuation, whereas the morphological primes were noun phrases of professions that had predominantly HA or LA interpretations. The prime materials in Experiment 2 were a subset of the ones used in Experiment 1.

The target items were noun phrases that were judged to be relatively ambiguous in a pilot experiment (e.g., “Russian teacher”). On a 1–7 Likert scale (with 1 meaning the given noun phrase can only have the LA interpretation, e.g., “someone who teaches and is of Russian descent”; and 7 only the HA interpretation, e.g., “someone who teaches the Russian language”), we selected eight noun phrases (out of 48 in the pilot) with mean ratings closest to the midpoint of the scale (mean ratings ranged from 3.19 to 4.65) and relatively high variance in ratings (standard deviations ranged from 1.97 to 2.52). These two features of the selected items maximized the chance of the interpretations of these noun phrases being influenced depending on the preceding prime, if there was indeed any priming effect.

The pilot experiment had the same design as Experiment 2 (described below). The main difference was that the pilot included 48 target items, many of which we eliminated due to participants having an extremely strong preference for one interpretation. For example, we eliminated “animal activist” due to a strong preference for the HA interpretation (a mean rating of 6.82, $SD = 0.44$, in favor of the interpretation “someone who advocates for animal rights”), as opposed to the LA interpretation (“an animal who advocates for a cause”). After narrowing down to eight items by considering the mean and variability in ratings, we simulated new data using pilot data for those specific items to estimate the new sample size required by using the “simr” package.

Due to the difficulty in finding relatively ambiguous noun phrases, there were only eight target trials in Experiment 2. That is, there were four sentence and four morphological primes (equal split of HA and LA), paired with eight morphological target items. Participants were randomly assigned to one of four counterbalancing lists, in which the Prime Type and Prime Attachment for each target item were counterbalanced across lists. The full list of prime and target materials for Experiment 2 can be found in Appendix B.

Procedure

The experiment was a typed experiment hosted on Qualtrics. Participants completed the experiment online without supervision.

Each trial consisted of a prime and a target task. The prime was either a sentence or a morphological prime, which was manipulated to have either a high (HA) or low (LA) attachment structural organization. Participants were given instructions to perform a sentence continuation task and a semantic judgment task, but they were not informed of the prime-target manipulation. For sentence continuation, participants were instructed to type a response that formed a complete sentence whenever they were presented with a sentence fragment. This task served as the sentence prime. For semantic judgment, participants were instructed to rate the likelihood of the possible meanings of noun phrases on a 1–7 Likert scale (with 1 meaning the given noun phrase can only have the LA interpretation, and 7 only the HA interpretation). When participants were asked to rate noun phrases with predominant meanings, this task served as the morphological prime (and to validate the manipulation; see below); when participants were asked to rate relatively ambiguous noun phrases, this task served as the target task.

To summarize, when the participant completed a trial with a sentence prime, they first completed a sentence with attachment-biasing agreement features, then gave a semantic judgment for an ambiguous noun phrase. If the participant completed a trial with a morphological prime, they first rated a noun phrase with a predominant meaning, then rated an ambiguous noun phrase. Because the semantic judgment task specifically required participants to think about the possible meanings of the morphological primes and targets, it resolved the limitation presented by Experiment 1.

Coding and analyses

Prime responses that were incompatible with our intended prime attachment manipulation (i.e., when participants ignored the sentence agreement features, rated LA primes as 4 or above, or HA primes as 4 or below) were deemed invalid and left out of our analyses, leaving 1,661 (out of 2016; 82 %) analyzable trials in total. The ratings for valid target responses (1–7) were then transformed into z-score units using by-subject means and standard deviations to account for individual differences in how participants use scales and susceptibility to priming.

We built a linear mixed effects model with the dependent variable being the rating for each trial in z-score units, in order to analyze the attachment preference for ambiguous noun phrases as a function of Prime Type (sentence or morphological), Prime Attachment (HA or LA), and their interaction. Fixed effects were sum-coded. Although we attempted to use the maximal random effects structures, we removed all random slopes due to convergence issues. We also removed the participant random intercept due to convergence issues and by-participant variance estimates of 0. Because the response variable was z-scored within a participant, it was not surprising that there was very little variation between participants.

Post-hoc Bayesian analyses

We fit Bayesian mixed effects models using the same specifications and approach as Experiment 1, except where noted below. The dependent variable in Experiment 2 was the z-scored rating for ambiguous noun phrases, so we used linear mixed effects models with a Gaussian distribution and an identity link function. We fit five models for our main analysis: a full model with Prime Type and Prime Attachment as fixed effects and their interaction, a model without the interaction term, a model with only Prime Type, a model with only Prime Attachment, and an intercept-only model. We fit four models for the follow-up planned comparisons. Within each prime type, we fit models with and without prime attachment as a fixed effect.

Results and discussion

Fig. 2 shows the mean rating for ambiguous noun phrases (in z-score units) following HA or LA sentence or morphological primes. On average, participants rated ambiguous noun phrases following HA primes 0.09 z-score units higher than following LA primes (the main effect of Prime Attachment was significant; $\beta = -0.11$, $SE = 0.04$, $z = -2.61$, $p = .009$). However, this was likely driven by the morphological primes; there was a significant Prime Type × Prime Attachment interaction ($\beta = 0.18$, $SE = 0.18$, $z = 2.10$, $p = .036$). Participants rated ambiguous noun phrases similarly following HA sentence primes ($M = -0.02$, $SE = 0.19$), compared to following LA sentence primes ($M = 0.01$, $SE = 0.19$); the pairwise comparison was not significant ($t = 0.34$, $p = .73$). In contrast, participants rated ambiguous noun phrases 0.21 z-score units higher following HA morphological primes ($M = 0.16$, $SE = 0.19$), compared to LA sentence primes ($M = -0.05$, $SE = 0.19$), and this pairwise comparison was significant ($t = 3.50$, $p = .0005$).

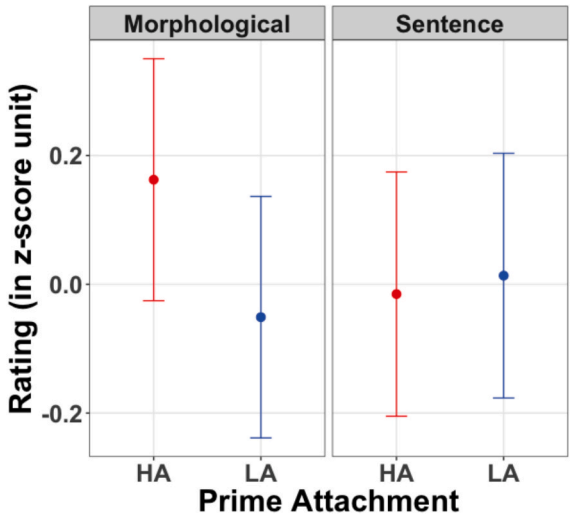


Fig. 2. Mean rating (in z-score unit) for ambiguous noun phrases following high- or low-attachment morphological or sentence primes, color-coded by prime attachment and separated into two panels by prime type. Higher means more likely to accept high-attachment reading only. Error bars represent standard errors.

Parallel Bayesian analyses were consistent with our frequentist results. The computed Bayes Factor was inconclusive regarding the Prime Type × Prime Attachment interaction ($\beta = 0.18$, 95 % CI = [0.01, 0.34], $BF_{10} = 0.386$). Taken together with the significant effect in our frequentist analysis, we interpret the interaction as marginally significant. Follow-up planned comparisons revealed strong evidence for an effect of Prime Attachment for morphological primes ($\beta = -0.20$, CI = [-0.31, −0.09], $BF_{10} = 15.70$) and strong evidence against an effect of Prime Attachment for sentence primes ($\beta = -0.02$, CI = [-0.15, 0.10], $BF_{10} = 0.033$).

Evidence was inconclusive with regards to a main effect of Prime Attachment ($\beta = -0.12$, 95 % CI = [-0.20, −0.04], $BF_{10} = 1.04$) and strongly against a main effect of Prime Type ($\beta = -0.04$, 95 % CI = [-0.12, 0.05], $BF_{10} = 0.031$).

To summarize, Experiment 2 showed stronger evidence that only morphological (but not sentence) attachment preference affected later ambiguous noun phrase interpretation. Along with the results in Experiment 1, our results suggest that structuring mechanisms are not shared across grain size.

One alternative interpretation for the results of Experiment 1 and 2 is that the patterns simply reflected task priming (i.e., sentence completion primes sentence completion and semantic interpretation primes semantic interpretation) rather than priming within linguistic units of the same grain size. Specifically, Experiment 1 showed that sentence completion (but not morphological recall) primed sentence completion, and Experiment 2 showed that semantic interpretation (but not sentence completion) primed semantic interpretation. In other words, the target task and grain size were confounded. To control for the possibility of task priming, we ensured that all tasks were semantic interpretation tasks in Experiment 3. Additionally, the target task was always sentence production in Experiment 1 and noun phrase semantic interpretation in

Experiment 2 regardless of the prime type, which led to participants experiencing more trials of a particular grain size in each experiment. In Experiment 3, we assessed semantic interpretation of both sentences and noun phrases in the target task.

Experiment 3

Method

Participants

Two hundred and sixty-two undergraduates from the University of California San Diego participated in exchange for course credit. Ten participants were excluded who either did not produce more than 50 % valid data (see Coding and Analyses for criteria) or otherwise did not complete the experiment due to technical issues. The remaining two hundred and fifty-two participants indicated that they were native English speakers.

Materials

To address concerns of task priming and imbalanced numbers of trials for different grain sizes in previous experiments, we used a within-subjects 2 (Prime Attachment: High or Low) × 2 (Prime Type: Sentence or Morphological) × 2 (Prime-Target Pairing: Same or Different grain size) design. Consistent with previous experiments, each trial contained a prime and target pair, and the prime was either a sentence or a noun phrase of an HA or LA organization. Unlike previous experiments, the grain size of the linguistic unit in the target was not held constant. Instead, it was an equal split between sentence and noun phrase targets. That is, the Same Prime-Target Pairing condition included trials in which the prime and target were both sentences, or both noun phrases; the Different Prime-Target Pairing condition included trials where a noun phrase target was primed by a sentence, or where a sentence target was primed by a noun phrase.

The sentence primes were similar to the materials in Experiments 1 and 2. Instead of sentence fragments, we presented participants with complete sentences that utilized agreement features to coerce HA or LA meanings in Experiment 3, such as "The boy teased the hamsters of the girl that were running around (HA)/who was an animal advocate (LA)". The morphological primes were identical to the materials of Experiment 2 (i.e., noun phrases with predominantly HA or LA meanings).

The sentence targets were complete sentences with ambiguous agreement features, such that both HA and LA meanings were plausible. For instance, in "someone shot the servant of the actress who was on the balcony", it is unclear who was on the balcony (i.e., both "the servant" and "the actress" are plausible). The morphological targets were relatively ambiguous noun phrases identical to the materials in Experiment 2.

There were eight sentence primes and eight morphological primes, with an equal split between HA and LA structures. They were paired with eight sentence and eight morphological targets. That is, each participant completed 16 trials in total. Participants were randomly assigned to one of four counterbalancing lists, in which the prime type and attachment that preceded each target were counterbalanced. The full list of prime and target materials for Experiment 3 can be found in Appendix C.

Procedure

The experiment was a typed experiment hosted on Qualtrics. Participants completed the experiment online without supervision.

The task in Experiment 3 was a semantic judgment task, regardless of whether participants were responding to a sentence or a noun phrase, and whether the item served as a prime or a target. Participants were instructed to first memorize the item on the screen, then to perform a semantic judgment task with a 1–7 Likert scale (with 1 meaning the LA interpretation was possible and 7 meaning only the HA interpretation was possible) on the next page. For example, when presented with the HA sentence prime "the boy teased the hamsters of the girl that were running around", participants first attempted to memorize the sentence and advanced to the next page when ready. Then, when prompted with the question "Who was/were running around?", participants rated on a scale of 1–7 the likelihood of the interpretation being "the girl" (LA; 1 on the scale) or "the hamsters" (HA; 7 on the scale).

In the Same Prime-Target Pairing condition, participants rated an unambiguous sentence prime (HA or LA meaning) followed by an ambiguous sentence target, or rated an unambiguous noun phrase prime (HA or LA) followed by an ambiguous noun phrase target. In the Different Prime-Target Pairing condition, participants rated an unambiguous sentence prime followed by an ambiguous noun phrase target, or rated an unambiguous noun phrase prime followed by an ambiguous sentence target. Because both prime types operated under a semantic interpretation task, this design helped us rule out the possibility that the pattern priming effects revealed in Experiments 1 and 2 were due to task-specific priming. That is, given that all primes are now in the same task, if the structuring mechanisms are indeed not shared across grain sizes, we should only observe priming effects in the Same but not Different Prime-Target Pairing conditions.

Coding and analyses

Prime responses that were incompatible with our intended prime attachment manipulation (i.e., when participants rated LA primes as 4 or above, or HA primes as 4 or below) were deemed invalid and left out of our analyses, leaving 3653 (out of 4032 trials; 90 %) analyzable trials in total. The ratings for valid target responses (1–7) were then transformed into z-score units using by-subject means and standard deviations to account for individual differences in how participants used scales and susceptibility to priming.

In the main analysis, we built a linear mixed effects model with the dependent variable being the rating for each trial in z-score units, in order to analyze the attachment preference of ambiguous target items as a function of Prime Attachment (HA or LA), Prime-Target Pairing (Same or Different), and their interaction. The random effects structure included a by-item intercept. Consistent with Experiment 2, we removed random slopes and the intercept for participants due to convergence issues and small participants variability after z-scoring. This analysis allowed us to confirm whether there was a baseline attachment priming effect, and whether such an effect was unique to linguistic units of the same grain size.

In a secondary analysis, we added to the original linear mixed effects model. The dependent variable was still the rating for each trial in z-score units, whereas the independent variables were Prime Type (Sentence or Morphological), Prime Attachment (HA or LA), Prime-Target Pairing (Same or Different), as well as all two-way and three-way interactions. Fixed effects were sum-coded. The random effects structure was the same as above. This analysis lent insights into whether the priming effects (if any) differed for sentence versus morphological items.

Post-hoc Bayesian analyses

Our model fitting procedures were nearly identical to Experiment 2, except where noted below. Our first analysis involved a model with Prime-Target Pairing, Prime Attachment, and their interaction with a by-item random intercept. We then built four additional nested models: a model with Prime-Target Pairing and Prime Attachment but no interaction, a model with only Prime-Target Pairing, a model with only Prime Attachment, and an intercept-only model. For the second analysis, we fit a model with Prime-Target Pairing, Prime Attachment, and Prime Type as well as all two-way interactions and a three-way interaction between Prime-Target Pairing, Prime Attachment, and Prime Type. Our goal with this model was to assess whether the interaction between Prime-Target Pairing and Prime Attachment further differs across morphological and sentential prime types, so we only tested for the three-way interaction with Bayesian analyses.

Results and discussion

Fig. 3 shows the mean ratings for ambiguous target items (in z-score units) following HA or LA primes of same or different prime-target pairing. On average, when the prime and target were of the same grain size, the ratings were 0.17 z-score units higher than when the prime and target were of different grain sizes (the main effect of Prime-Target Pairing was significant; $\beta = 0.18$, $SE = 0.03$, $t = 5.16$, $p < .001$).

To address whether attachment priming was specific to linguistic units of the same grain size only, we turned to the main effect of Prime Attachment and the Prime Attachment × Prime-Target Pairing interaction. The average ratings for target items following HA and LA primes were comparable (i.e., no main effect of Prime Attachment; $\beta = -0.03$, $SE = 0.03$, $t = -1.30$, $p = .19$). However, when grain size was taken into account, we found that priming effect was present among linguistic units of the same grain size but not among units of different grain sizes (i.e., a significant Prime Attachment × Prime Target Pairing interaction; $\beta = -0.20$, $SE = 0.06$, $t = -3.43$, $p < .001$). Specifically, when the prime and the target were of the same grain size, there was a 0.12 z-score units difference in ratings for target items following HA primes ($M = 0.14$, $SE = 0.09$) versus LA primes ($M = 0.02$, $SE = 0.09$); the pairwise comparison was significant ($z = 3.39$, $p < .001$). However, when the prime and the target were of different grain sizes, the ratings following HA ($M = -0.12$, $SE = 0.09$) and LA primes ($M = -0.05$, $SE = 0.09$) were comparable; the pairwise comparison was not significant ($z = -1.49$, $p = .14$).

Post-hoc Bayesian analyses replicated and extended our frequentist results. We observed a main effect of Prime-Target pairing ($\beta = 0.18$, 95 % CI = [0.12, 0.24], $BF_{10} = 1.91 \times 10^6$) and an interaction between Prime-Target pairing and Prime Attachment ($\beta = -0.20$, 95 % CI = [−0.32, −0.09], $BF_{10} = 10.46$). There was evidence against a main effect of Prime Attachment ($\beta = -0.05$, 95 % CI = [-0.10, 0.01], $BF_{10} = 0.049$). Follow-up comparisons show evidence for a main effect of Prime Attachment when grain size is the same ($\beta = -0.14$, CI = [-0.22, −0.06], $BF_{10} = 5.56$) and evidence against a main effect of Prime Attachment when grain size is different ($\beta = 0.06$, CI = [-0.02, 0.14], $BF_{10} = 0.062$).

In our secondary analysis, we added the variable of Prime Type into the model to examine whether the priming effect was modulated by whether the prime was a sentence or a noun phrase. Fig. 4 further breaks down Fig. 3 into the two prime types. In regards to results involving the new addition of Prime Type, we only found a marginal Prime Type × Prime-Target Pairing interaction ($\beta = -0.71$, $SE = 0.36$, $t = -1.94$, $p = .07$), such that the average ratings for morphological targets were 0.54 z-score units higher when the primes were also morphological, compared to when the primes were sentences ($z = -2.91$, $p = .003$). The ratings for sentence targets were comparable when primes were of the same or different grain size (−1.70 z-score units difference; $z = 0.92$, $p = .36$).

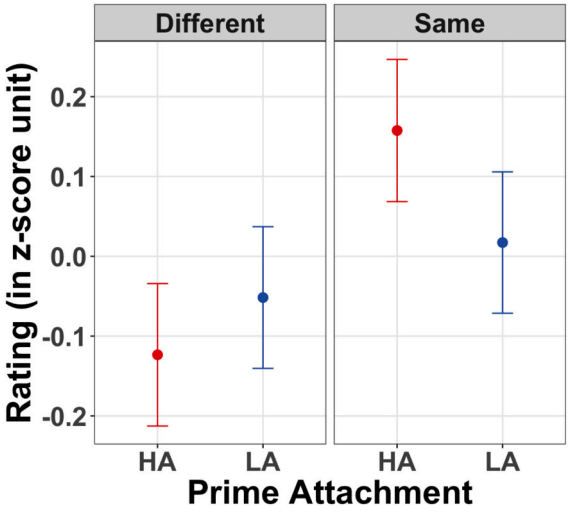


Fig. 3. Mean rating (in z-score unit) for ambiguous target items following high- or low-attachment primes, color-coded by prime attachment and separated into two panels by prime-target pairing. Higher means more likely to accept high-attachment reading only. Error bars represent standard errors.

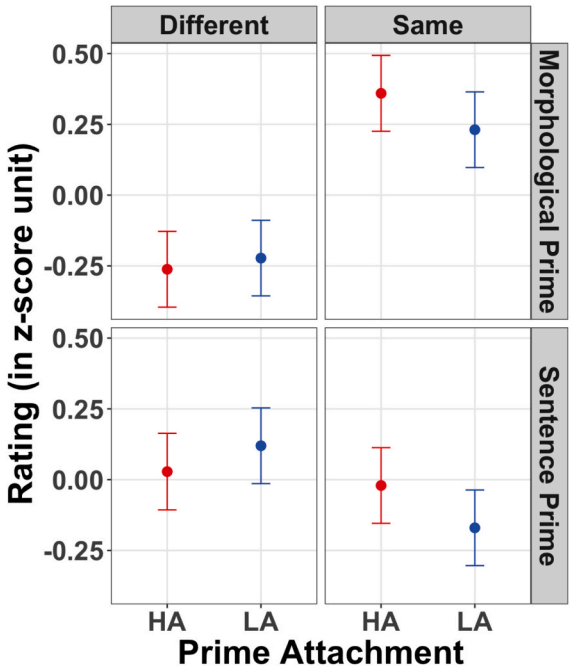


Fig. 4. Mean rating (in z-score unit) for ambiguous target items following high- or low-attachment primes, color-coded by prime attachment and separated into four panels by prime-target pairing and prime type. Higher means more likely to accept high-attachment reading only. Error bars represent standard errors.

Critically, there was no main effect of Prime Type, Prime Attachment × Prime Type interaction, nor Prime Attachment × Prime-Target Pairing × Prime Type interaction. The main effect of Prime-Target Pairing reported in the main analysis remained significant after adding Prime Type to the model ($\beta = -0.18$, $SE = 0.03$, $t = 6.27$, $p < .001$), as did the interaction between Prime-Target Pairing and Prime Attachment ($\beta = -0.20$, $SE = 0.06$, $t = -3.48$, $p < .001$). In other words, there was no evidence to suggest that the priming effects we reported were dependent on whether the prime was a sentence or a noun phrase.

Our second set of Bayesian analyses involved testing whether there was a three-way interaction between Prime Type, Prime Attachment, and Prime-Target Pairing. Bayes Factor comparisons produced evidence against such an interaction ($\beta = -0.07$, 95 % CI = [-0.31, 0.16], $BF_{10} = 0.073$). We also obtained Bayes Factor evidence in favor of a Prime Attachment × Prime-Target Pairing interaction, consistent with our main analysis ($\beta = -0.20$, CI = [-0.32, −0.09], $BF_{10} = 11.34$).

Taken together, we found evidence suggesting that attachment priming most likely only occurs when the prime and target were linguistic units of the same grain size. That is, structuring mechanisms are likely not shared between the sentence and the morphological level.

General discussion

In three experiments, the current work investigated whether the structuring mechanisms for linguistic units of different grain sizes are shared. Specifically, we tested whether relative clause attachment in sentences and morphological attachment in noun phrases shared structuring mechanisms and thus showed bidirectional priming effects. We used a variety of tasks throughout the experiments, but priming was generally operationalized throughout as whether participants were more likely to produce or interpret a relatively attachment-neutral target item with high attachment (HA) bias following the production

or comprehension of an HA prime, compared to following producing or interpreting a low attachment (LA) prime. Based on previous work on structural priming in relative clause sentences (e.g., Desmet & Declercq, 2006; Scheepers, 2003), we expected to replicate this priming effect within the same grain size at least on the sentence level. At the time of the completion of our work, we were not aware of any previous work showing within-domain priming on the morphological level among ambiguous noun phrases (only cross-domain priming from math to adjective-noun-noun compounds in Scheepers & Sturt, 2014). However, we expected to see the priming effect from noun phrases to other noun phrases if such an effect extends beyond the sentence level (i.e., priming should be observed in any linguistic units that indeed have similar underlying structures despite differences in surface features and meanings). Critically, if the structuring mechanisms were shared across grain sizes, we should see attachment priming from sentences to noun phrases, and vice versa. If the mechanisms were distinct, then we should see within-level priming as described above only.

Experiment 1 examined whether attachment preferences in relative clause sentence production and in free recall of noun phrases affected subsequent relative clause sentence production. The results showed that participants were numerically more likely to produce HA relative clause sentences following HA primes (compared to following LA primes), but a marginal interaction (and the accompanying pairwise comparisons) suggested that this should only be taken as suggestive evidence that the effect was most likely driven by the sentence primes. That is, we replicated the relative clause priming effect reported in the literature but found no strong evidence that noun phrases could prime sentence production. However, to establish that there is no cross-grain size priming, we needed to establish a double dissociation. Moreover, it was unclear at that point whether noun phrases could produce priming effects at all, even within-level. If there is no cross-grain size priming, the result should be bi-directional.

Experiment 2 examined whether attachment preferences in relative clause sentence production and in noun phrase comprehension affected subsequent noun phrase comprehension. The results demonstrated that participants rated the HA interpretation of an ambiguous noun phrase as more probable following an HA prime (compared to following an LA prime), but the patterns were mostly driven by the morphological primes. These patterns are important in two different ways: First, we presented novel evidence showing that structural priming effects within the linguistic domain extend beyond the sentence level to ambiguous noun phrase comprehension. Second, morphological (but not sentence) attachment preferences affected subsequent morphological attachment preferences. Crucial to the question of the sharedness of structuring mechanisms across linguistic units of different grain sizes, the combination of the results in Experiment 1 and 2 resembled a double dissociation, suggesting that the mechanisms are distinct.

However, the interpretation of Experiments 1 and 2 is challenged by the fact that because the tasks for the two linguistic levels were different, our results could have been explained by preferences in sentence continuation priming sentence continuation but not semantic interpretation, and vice versa, regardless of grain size. As such, Experiment 3 sought to confirm the double dissociation and to eliminate the possibility of explaining the dissociation via task priming by holding the tasks across grain sizes constant (i.e., all tasks were semantic interpretation tasks).

Experiment 3 compared whether attachment preferences in sentence and morphological comprehension affected subsequent comprehension preferences in the same versus different linguistic level. The results showed that attachment priming was indeed only present in linguistic units of the same grain size. Further analysis found no evidence suggesting any difference in priming magnitude for different grain sizes, meaning that the results are unlikely to be driven by one particular grain size. Additionally, prime and target tasks for all conditions were the same, so the results could not be reduced to task priming. Altogether, the results from three experiments suggested that structuring mechanisms for linguistic units of different grain sizes are not shared.

Given the evidence for cross-domain priming in the literature (e.g., Scheepers et al., 2011; Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016), it is somewhat surprising that we failed to observe cross-grain size priming within the linguistic domain. Our main goal with these experiments was to explore cross-domain priming within language systems rather than outside of them, and so we can only speculate as to why there is evidence in the literature that mathematics and music prime relative clause attachment, but morphological organization does not (and why relative clause attachment does not prime morphological organization).

One straightforward possibility is that processes that underlie morphological organization themselves are isolated from influences of processes that drive structural organization outside the morphological system. In addition to being consistent with the current results, this possibility predicts that manipulations of morphological organization should fail to prime or be primed by the non-linguistic systems of organization that have been shown to affect relative-clause attachment (namely, music and math).

An observation relevant to the possible isolability of the processes that organize morphological representations comes from Scheepers and Sturt (2014). They showed that the structural organization of math problems (e.g., 25–4 × 3, which is right-branching, vs. 25 × 4–3, which is left-branching) affected how adjective-noun-noun phrases were interpreted (*bankrupt coffee dealer*, which is right branching, vs. *organic coffee dealer*, which is left-branching), and vice versa. Two considerations potentially limit the informativeness of this result with respect to the claim here of the potential isolation of morphological processes. First, as with relative clauses (as noted next), it is possible that a level of organization outside of morphology affects performance (e.g., rhythm, prosody) in both the linguistic and nonlinguistic domains, which is less likely to be true with respect to the level of morphology at stake here (e.g., Russian teacher). Second, it is reasonable to posit that the structural organization of an adjective-noun-noun sequence is at a syntactic level, unlike the organization that distinguishes the interpretations of the morphological structural alternatives here. In all, further research is needed to directly address this point.

More generally, the possible isolability of the processes that determine the type of morphological organization investigated here has not (to our knowledge) been addressed in the broader psycholinguistic literature (indeed, filling just this gap was a main objective of this project). Most investigations of the processes that determine morphological organization have focused on more traditional questions of, for example, whether morphology operates in a structurally independent manner (separately from phonology or semantics; e.g., Dohmes, Zwitserlood, & Bölte, 2004; Koester & Schiller, 2008; Zwitserlood, Bölte, and Dohmes, 2000). This literature generally suggests that morphological processing can be characterized as operating in a structurally independent way, which is consistent with, but does not necessarily require, a system isolated from external influences.

A different (but perhaps related) possibility about which we can only offer vague speculations is that relative-clause attachment, mathematics, and music may share some organizational component that is not shared with morphological organization. For example, it may be that some rhythmic, prosody-like process (e.g., Jun & Bishop, 2015) operates in relative-clause attachment, mathematics, and music but not during morphological organization. Or, relative-clause attachment, mathematics, and music may share some less-superficial level of organization that is more abstract and general (i.e., global configuration and shape).

Finally, it is worth noting that cross-domain structural priming may be highly sensitive to nuances in processing. For example, Scheepers et al. (2011) did not observe math priming in participants who were explicitly reminded of the operator-precedence rules before the experiment, which may have encouraged them to strategically direct their attention towards searching for the multiplication and division operators. The authors speculated that explicit instruction dampened priming

effects due to these effects being relatively dependent on implicit processing. In terms of the online processing dynamics of words versus sentences, it is possible that high frequency noun phrases and words have "larger chunks" of stored meanings, whose semantics are not computed by assembling each morpheme on-the-fly in ways comparable to how comprehenders identifies what entity a relative clause modifies in real-time (although such a possibility fails to explain why the current experiments found priming from morphology to morphology). Thus, low frequency morphological items or a task that requires participants to create new words and phrases may offer a promising avenue into furthering our understanding of the processing of morphological structures.

The current work ultimately demonstrates within-level linguistic attachment priming in comprehension, but a few modality-specific research questions remain unanswered. On the sentence level, there is evidence that distributional patterns in relative clause production are linked to comprehension performance. For example, Gennari and MacDonald (2009) reported compatible production preferences in both experiments and corpora, showing that passive structures were more likely to be produced with theme-experiencer verbs than with agent-theme verbs, and when two nouns mismatched in animacy than when were both animate. Critically, they also showed that passive production rates predicted reading times in comprehending active object relative clauses, with more commonly passivized verb type and animacy configurations in production being associated with more comprehension difficulties in an active relative clause. While sentence production distributional patterns and comprehension performances are linked, due to the difficulty in designing a production task on the morphological level, it is unclear whether noun phrase production affects subsequent noun phrase production or comprehension.

Aside from innovating ways to measure morphological production, future work may also specify how the structuring mechanisms for different linguistic units differ, and further explore how these non-shared mechanisms are integrated in online production and comprehension. In the interest of keeping the results and the experimental logic comparable to previous work in the generality of structuring mechanisms, the current work chose to use specific test cases of linguistic ambiguity coupled with a structural priming paradigm, which allowed for clear predictions of behaviors. Although ambiguity is ubiquitous in everyday language use, speakers and comprehenders do not always detect it because their prior knowledge and linguistic biases often help them convey or derive the intended meaning effectively. For instance, in the case of relative clause attachment, English speakers tend to have a low attachment preference in production (as shown in our data and previous work, e.g., Scheepers et al., 2011), and other semantic cues in discourse may aid in comprehension. Additionally, our pilot data indicated that comprehenders often have strong interpretation preferences for noun phrases that could have more than one plausible meanings due to attachment ambiguity (which led to the small number of morphological target items in our experiments). It is unclear whether there is a clear morphological attachment preference in noun phrases and multimorphemic words in the English language as a whole, and whether that preference aligns with the low attachment preference in sentences. And if so, how do cognitive factors (such as memory and attentional constraints) guide those statistics? In Scheepers and Sturt (2014)'s data, sensibility ratings tended to be higher for right-branching than for left-branching adjective-noun-noun compounds, though it is unclear in what the preference would be in noun phrases like our materials where both HA and LA alternatives are right-branching. Corpus studies with attachment statistics on the morphological level and comparisons with statistics on the sentence level will lend important insights into the universality of cognitive biases in language use.

To conclude, the current study used attachment ambiguity and priming to investigate the sharedness of structuring mechanisms for linguistic units of different grain sizes, namely relative clause sentences and noun phrases. Based on results across three experiments showing that priming was only observed between linguistic units of the same grain size, we concluded that the structuring mechanisms on the sentence level and the morphological level are likely not shared.

CRediT authorship contribution statement

Sin Hang Lau: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Janna W. Wennberg:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Victor S. Ferreira:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Full Lists of Prime and Target Materials in Experiment 1

Table A1
Prime materials (presented in the specified counterbalanced and pseudorandomized order).

Item	HA Prime	LA Prime
1	3 + (6 − 2)/2 =	3 + 6 − 2/2 =
2	10 + (7 − 5) × 3 =	10 + 7 − 5 × 3 =
3	41 − (8 + 3) × 3 =	41 − 8 + 3 × 3 =
4	20 + (32 – 6)/2 =	20 + 32 – 6/2 =
5	56 – (5 + 3) × 4 =	56 – 5 + 3 × 4 =
6	31 + (8 – 5) × 2 =	31 + 8 – 5 × 2 =
7	43 – (27 – 9)/3 =	43 – 27 – 9/3 =
8	19 + (24 – 8)/4 =	19 + 24 – 8/4 =
9	90 – (5 + 15)/5 =	90 – 5 + 15/5 =
10	78 – (9 + 6) × 2 =	78 – 9 + 6 × 2 =
11	45 – (10 + 5) × 3 =	45 – 10 + 5 × 3 =
12	70 – (25 + 5)/5 =	70 – 25 + 5/5 =
13	80 − (9 + 1) × 5 =	80 − 9 + 1 × 5 =
14	67 − (24 − 12)/3 =	67 − 24 − 12/3 =
15	7 + (28 − 4) × 2 =	7 + 28 – 4 × 2 =

(*continued on next page*)

Table A1 (*continued*)

Item	HA Prime	LA Prime
16	9 + (20 + 10)/5 =	9 + 20 + 10/5 =
17	15 – (12 – 4)/2 =	15 – 12 – 4/2 =
18	2 + (8 + 4) × 3 =	2 + 8 + 4 × 3 =
19	85 – (14 + 21)/7 =	85 – 14 + 21/7 =
20	10 + (6 + 3) × 2 =	10 + 6 + 3 × 2 =
21	56 + (6 + 6)/2 =	56 + 6 + 6/2 =
22	4 + (22 – 4)/2 =	4 + 22 – 4/2 =
23	98 – (50 – 30)/10 =	98 – 50 – 30/10 =
24	12 + (26 – 1) × 4 =	12 + 26 – 1 × 4 =
25	social psychologist	careless psychologist
26	political scientist	poor scientist
27	criminal lawyer	stubborn lawyer
28	quantitative analyst	wealthy analyst
29	pure mathematician	talkative mathematician
30	standup comedian	boring comedian
31	classical musician	creative musician
32	primate researcher	diligent researcher
33	marine biologist	adventurous biologist
34	organic chemist	angry chemist
35	electrical engineer	lazy engineer
36	nuclear physicist	meticulous physicist
37	Gabriel cut the tags of the shirt that were (HA)/that was (LA)___.	
38	Everyone stared at the mansion of the millionaire that was (HA)/who was (LA)___.	
39	The witness recognized the driver of the vehicle who was (HA)/that was (LA)___.	
40	The recruiters discussed the performance of the candidates that was (HA)/who were (LA)___.	
41	We consulted the accountants of the bank who were (HA)/that was (LA)___.	
42	Martin hugged the pets of the school friend that were (HA)/who was (LA)___.	
43	The storm destroyed the stairs of the house that were (HA)/that was (LA)___.	
44	Hans cleaned the windows of the pharmacy that were (HA)/that was (LA)___.	
45	The boy teased the hamsters of the girl that were (HA)/who was (LA)___.	
46	Frank thought of the brothers of the friend who were (HA)/who was (LA)___.	
47	The voters supported the policies of the politician that were (HA)/who was (LA)___.	
48	The firefighters saved the occupants of the penthouse who were (HA)/that was (LA)___.	
49	Maria consoled the friends of the roommate who were (HA)/who was (LA)___.	
50	Peter heard the birds of the girl that were (HA)/who was (LA)___.	
51	The police interrogated the suspect of the crimes who was (HA)/that were (LA)___.	
52	Judith prosecuted the owner of the animals who was (HA)/that were (LA)___.	
53	Peter used the printers of the department that were (HA)/that was (LA)___.	
54	Someone shot the cousins of the actress who were (HA)/who was (LA)___.	
55	Frida complained to the butchers of the supermarket who were (HA)/that was (LA)___.	
56	The gardener mowed the lawns of the park that were (HA)/that was (LA)___.	
57	The patient contacted the head physician of the neurologists who was (HA)/who were (LA)___.	
58	Leo pointed to the drawings of the old man that were (HA)/who was (LA)___.	
59	The portraitist painted the grandparents of the king who were (HA)/who was (LA)___.	
60	The officer searched the house of the criminals that was (HA)/who were (LA)___.	

Note. Participants saw either the HA or the LA version of items 1–24 and 37–60. Due to the scarcity of appropriate morphological items, participants saw both HA and LA versions of items 25–36. As a result, there were 72 primes in total.

Table A2
Target materials.

Item	Target Fragment
1	The philanthropist drove the limo of the charities that___.
2	They were shocked by the paragraphs of the essay that___.
3	The hairdresser helped the stylist of the celebrities who___.
4	John met the supervisor of the employees who___.
5	The bus driver talked to the leader of the boy scouts who___.
6	The writer deleted the lines of the poem that___.
7	The hacker attacked the websites of the service provider that___.
8	Klara interviewed the mentees of the mentor who___.
9	The commission referred to the source of the donations that___.
10	The broker communicated with the agent of the buyers who___.
11	The thief stole the documents of the organization that___.
12	The volunteer bathed the kittens of the cat that___.
13	The barista broke the parts of the machine that___.
14	Kurt distributed the tickets of the show that___.
15	The frost ruined the harvest of the fruit farms that___.
16	The tutor advised the students of the lecturer who___.
17	The personal trainer adjusted the settings of the treadmill that___.
18	The security guard comforted the visitor of the tenants who___.
19	The mover called the landlord of the customers who___.
20	The homeowner kept the letters of the office that___.

(*continued on next page*)

Table A2 (*continued*)

Item	Target Fragment
21	Ben attacked the boss of the workers who___.
22	The expert praised the investor of the young entrepreneurs who___.
23	The manager waited for the musicians of the pop star who___.
24	The train conductor criticized the kid of the passengers who___.
25	The mover insured the furniture of the apartments that___.
26	The superintendent checked the earnings of the company that___.
27	The florist befriended the servant of the princesses who___.
28	We were amused at the articles of the newspaper that___.
29	The reader insulted the partners of the editor who___.
30	The journalist stalked the dancers of the singer who___.
31	The scholar studied the language of the tribes that___.
32	The professor taught the daughters of the president who___.
33	The astronomer observed the stars of the spiral galaxy that___.
34	The farmer fed the calves of the cow that___.
35	Donna laughed at the apprentices of the designer who___.
36	The historians documented the stories of the city that___.
37	The dentist scraped the surface of the teeth that___.
38	The restaurant owner fired the helper of the chefs who___.
39	The researcher reviewed the debates in the field that___.
40	The marketing officer advertised the promotions of the month that___.
41	The businessman thanked the newcomer of the workers who___.
42	The knight slayed the dragons of the cavern that___.
43	The minister saw the bodyguard of the diplomats who___.
44	The lifeguard saved the toddler of the parents who___.
45	The tour guide mentioned the bells of the church that___.
46	The witch cursed the ancestors of the villager who___.
47	The pensioner complained about the content of the fliers that___.
48	The flower girl waved at the relatives of the bride who___.
49	The mermaid polished the diamonds of the ring that___.
50	Francesca corrected the supporters of the author who___.
51	The social worker greeted the nurse of the senior-citizens who___.
52	The botanist examined the roses of the garden that___.
53	The scientist criticized the method of the studies that___.
54	The woman stared at the decorations of the box that___.
55	The data scientists analyzed the strategies of the company that___.
56	The producer described the plot of the episodes that___.
57	The frost destroyed the products of the farm that___.
58	The public admired the doctor of the patients who___.
59	The protesters disagreed with the general of the soldiers who___.
60	The mechanic threatened the driver of the performers who___.
61	Nora visited the students of the piano teacher who___.
62	A stranger blackmailed the butler of the royals who___.
63	The housekeeper replaced the remote of the lights that___.
64	The secret service confiscated all files of the organization that___.
65	The programmer improved the software of the games that___.
66	The economist questioned the report of the businesses that___.
67	The reporter spoke to the captain of the players who___.
68	The neurologist operated on the mother of the twins who___.
69	The chauffeur met the representative of the state guests who___.
70	The concierge escorted the negotiator of the union members who___.
71	The pilot nodded at the head of the flight attendants who___.
72	The porter smiled at the children of the hotel resident who___.

Appendix B

Full Lists of Prime and Target Materials in Experiment 2.

Table B1
Prime materials (presented in the specified counterbalanced and pseudorandomized order).

Item	Prime Material
1	political scientist (HA)
2	marine biologist (HA)
3	skillful musician (LA)
4	careless psychologist (LA)
5	Frank thought of the brothers of the friend who were (HA)/who was (LA)___.
6	The recruiters discussed the performance of the candidates that was (HA) /who were (LA)___.
7	Hans cleaned the windows of the pharmacy that were (HA)/that was (LA)___.
8	The boy teased the hamsters of the girl that were (HA)/who was (LA)___.

Table B2
Target Materials.

Item	Target Material
1	baroque painter
2	fine artist
3	revolutionary scholar
4	Latin dancer
5	creative writer
6	canine detective
7	artistic gymnast
8	Russian teacher

Appendix C

Full Lists of Prime and Target Materials in Experiment 3.

Table C1
Prime materials (presented in the specified counterbalanced and pseudorandomized order).

Item	Prime Material
1	political scientist (HA)
2	marine biologist (HA)
3	primate researcher (HA)
4	criminal lawyer (HA)
5	skillful musician (LA)
6	careless psychologist (LA)
7	talkative mathematician (LA)
8	angry chemist (LA)
9	Frank thought of the brothers of the friend who were twins (HA)/who was sick (LA).
10	The recruiters discussed the performance of the candidates that was surprising (HA) /who were international students (LA).
11	Hans cleaned the windows of the pharmacy that were full of fingerprints (HA)/that was broken into (LA).
12	The boy teased the hamsters of the girl that were running around (HA)/who was an animal advocate (LA).
13	The farmer fed the calves of the cow that were crying (HA)/that was big and strong (LA).
14	The witness recognized the driver of the vehicle who had a suspended license (HA)/that was stolen (LA).
15	Everyone stared at the mansion of the millionaire that was renovated recently (HA) /who was generous (LA).
16	The priest spoke to the leader of the scouts who was dishonest (HA)/who were going camping (LA).

Table C2
Target materials.

Item	Target Material
1	baroque painter
2	fine artist
3	revolutionary scholar
4	Latin dancer
5	creative writer
6	canine detective
7	artistic gymnast
8	Russian teacher
9	John met the friend of the teacher who was in Germany.
10	Someone shot the servant of the actress who was on the balcony.
11	Andrew was speaking with the niece of the cleaner who was in Brazil.
12	The journalist interviewed the daughter of the colonel who had the accident.
13	The police arrested the sister of the porter who was in Melilla.
14	The boys poked fun at the son of the painter who was in the park.
15	My mother argued with the maid of the duchess who left the house.
16	Amilia exchanges letters with the cousin of the singer who was in the church.

Data availability

Already shared above.

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