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THEORETICAL/REVIEW

Structural priming during comprehension: A pattern from many pieces

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Abstract
Syntactic/structural priming has been shown to take place during comprehension. However, early comprehension findings revealed discrepancies with those in production, such as little to no abstract priming, yet readily observable lexically-mediated priming. These observations spurred important questions about whether structural processing is more lexically dependent during comprehension, whether abstract priming occurs at all during comprehension, and whether the mechanisms of structural facilitation are shared across these two modalities. The past decade has fortunately yielded many influential structural priming studies in comprehension, including those that seek to bridge the gap between structural processing across production and comprehension. This review serves to summarize recent findings that provide compelling evidence that abstract structural priming and learning do take place in comprehension, and that these effects show parity with those found in production. Competing mechanistic explanations of structural priming are also reviewed and considered in light of findings in both modalities. Lastly, a summary is provided that outlines future lines of inquiry needed to establish a better understanding of structural representation, priming, and learning in comprehension, and more generally.

Keywords Syntactic priming · Structural priming · Comprehension · Lexical boost

Syntactic priming: A window into our structural minds

The human cognitive system stores knowledge about the features and meanings of things, but critically, it also represents and stores information about how these things link together to form a structure. Such abstract structural representations provide the basis for imparting and extracting meaning, and so are critical to successful cognitive processing. However, their abstract nature also makes them more opaque to study empirically. This is highlighted in language processing, where non-meaning-based knowledge of structure (such as phonotactic, grammatical, prosodic, and metrical structure) are integral to successful communication, but involve processes that are very difficult to measure directly. However, the experimental study of structural representation and processing has advanced considerably in the past few decades, thanks in large part to structural priming studies (see Pickering & Ferreira, 2008, for a review), and the various paradigms they have contributed (e.g., Arai et al., 2007; Bock, 1986; Branigan et al., 2000; Pickering & Branigan, 1998; Potter & Lombardi, 1998). These paradigms involve some initial exposure to a sentence structure, either via a comprehension channel (such as listening, hearing, reading, or seeing an image) and/or a production channel. This initial exposure is considered "the prime" and its effect on the formulation/production/processing/parsing of a subsequent target sentence's structure provides the measure of "priming" observed for the given paradigm.

Beginning with Bock's (1986) foundational experiments on the production of syntax, it has been observed that experience with a given grammatical/syntactic structure (such as reading or saying a sentence with that structure) makes it more likely that this structure will be used in a subsequent utterance (relative to an alternative structure). For example, if someone says "The governess made a pot of tea for the princess," which has a prepositional object (ditransitive) structure, they are then more likely to describe a picture of a ditransitive event using the prepositional object structure, relative to after using the alternative, double object structure ("The governess made the princess a pot of tea"). This phenomenon is referred to as structural priming, syntactic priming, or structural persistence. This effect has been

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widely replicated and extended in the decades since its original discovery.

One important extension of this work is the observation that the general "abstract" priming effect is significantly increased when the prime and target sentences share the same verb (Pickering & Branigan, 1998). Using the above example, participants would be even more likely to describe a picture using the prepositional object (PO) structure after hearing the PO prime, if they are cued to re-use the prime verb ("made") in their target picture description. This increase in the magnitude of the priming effect has been termed the "lexical boost." More recent research has broadened observations of the lexical boost to include instances where any word that acts as a phrasal head is repeated across prime and target sentences (see Carminati et al., 2019, for an overview). The discovery of structural priming effects (both abstract priming effects and the lexical boost) have changed the game in terms of understanding syntactic representation and use (see Branigan & Pickering, 2017).

Structural priming research has been used to establish a stage of abstract structural processing during language production (e.g., Bock, 1986; Bock & Loebell, 1990; Pickering et al., 2002), provided evidence for shared representation of syntax across languages in the bilingual mind (e.g., Hartsuiker et al., 2004; Loebell & Bock, 2003; Schoonbaert et al., 2007), shed light on the development of syntactic representation in children (e.g., Huttenlocher et al., 2004; Savage et al., 2003) and second language learners (e.g., Hartsuiker & Bernolet, 2017), and provided theoretical mechanisms to account for this learning (e.g., Bock & Griffin, 2000; Chang et al., 2006; Pickering & Branigan, 1998; Reitter et al., 2011).

The success of Bock's (1986) approach led to an early abundance of similarly focused *production* studies, but relatively few complementary *comprehension* studies (see Pickering & Ferrieira, 2008, for a review). Here, I define a production study as a structural priming investigation where the target sentence is generated and produced by the participant (though the prime sentence can be comprehended or produced). A comprehension study, on the other hand, is a structural priming study where the prime and target sentences are comprehended (rather than produced), and the measure of structural priming is focused on an aspect of comprehension. For example, most comprehension studies measure on-going structural processing while participants read or listen to adjacent prime and target sentences. The prime sentence is manipulated to have either the same structure as the target or a different structure. Priming is indicated by facilitated processing of a target sentence (e.g., faster reading times, anticipatory eye movements to an expected referent in a visual array, changes in the BOLD (blood-oxygen-level-dependent) response, or changes in language-related event-related potential (ERP) components) following a prime with the same structure relative to a prime with a different structure.

When comprehension investigations began to emerge roughly 15 years ago, they revealed some interesting and potentially important deviations from effects observed in production (see Tooley & Traxler, 2010, for an early review). For example, early studies in comprehension observed little to no abstract priming (structural facilitation when the structure, but no content words were shared across prime and target sentences), but readily observed lexically mediated priming (structural facilitation when both the structure and the verb were shared between prime and target) (e.g., Arai et al., 2007; Carminati et al., 2008; Tooley et al., 2009). Furthermore, in the rare cases where abstract priming effects were obtained, the design/task/materials differed from the norm in potentially important ways, such as using multiple primes before the target (Thothathiri & Snedeker, 2008), using an act-out task that could invoke production processes (Thothathiri & Snedeker, 2008a, b), and using (non-obligatory) adjunct phrases as the focus of priming rather than verb arguments (Traxler, 2008).

These observations begged answers to essential questions about the nature of syntactic representation and processing, including whether structural processing is more lexically dependent during comprehension than production, whether abstract priming occurs during comprehension without the methodological scaffolding mentioned above, and whether the mechanisms of structural facilitation are shared across these two modalities. Answers to these questions have implications for all cognitive models of language processing, regardless of modality. Happily, the past 10 years have yielded many influential structural priming studies in comprehension. These advancements and their implications provide the focus of this review. In the following sections, I review this budding literature in relation to the important questions I mentioned above, methodological considerations of using structural priming paradigms, and the mechanistic accounts of structural priming effects. Finally, I lay out what I see as the necessary future lines of inquiry to address gaps in the literature and lead to a better understanding of the structural processes that subserve language use.

Abstract structure persists during sentence comprehension

Syntactic priming effects are groundbreaking in part because they provide evidence for a level of representation that is abstract, purely structural, and so can be separated from meaning- or sound-based representations. Couched within the framework of language production processes, the discovery of abstract structural priming effects, and initial findings from these studies, supported the presence

of a dedicated syntactic stage of processing, which in turn provided important advancements to cognitive models of language production (e.g., Bock, 1986; Bock & Loebell, 1990; Pickering et al., 2002). These important inferences are predicated on experimental manipulations where prime and target sentences share only structure (not content words), and the processing of the prime is shown to impact the structural choice or parse of the target sentence (and other sources of overlap can be ruled out). In production tasks, this manifests as an increase in the likelihood that an individual will use the same structure as a recently processed prime (relative to a possible alternative structure) to describe a subsequent, unrelated picture. A parallel result in comprehension would manifest as comprehension measures of a target sentence (such as the structural interpretation of an ambiguous sentence or a measure of processing difficulty) being modulated based solely on the structural overlap of a preceding prime sentence.

However, early studies on syntactic priming during comprehension found no such modulation of comprehension measures based only on the structural overlap between the prime and target sentences (Arai et al., 2007; Carminati et al., 2008; Tooley et al., 2009). Rather, comprehension processing measures of target structure were only impacted when there was both structural *and* lexical overlap between the prime and target sentences. If abstract syntactic priming does not occur during comprehension, which several early investigations deemed possible (but see Thothathiri & Snedeker, 2008; Traxler, 2008), then this could suggest the absence of a complementary dedicated structural processing stage during comprehension. Certainly, there are good reasons why comprehension processes, which rely on a series of sounds that must be structured to form words and phrases in order to extract the meaning of a message, might not be a mirror reverse of production processes. However, inferring there is no purely structural processing stage during comprehension (based on a lack of abstract priming effects) would be largely inconsistent with previous findings showing the outsized importance of syntactic information on initial comprehension processing (e.g., Ferreira & Clifton Jr., 1986; Frazier, 1987; Trueswell et al., 1994).

In short order, a handful of studies successfully obtained abstract priming effects (Thothathiri & Snedeker, 2008a, 2008b; Traxler, 2008), yet these studies used novel tasks or structures relative to the previous studies that had observed only lexically mediated priming effects (e.g., Arai et al., 2007; Branigan et al., 2005; Carminati et al., 2008; Ledoux et al., 2007; Tooley et al., 2009). More recently, a growing number of comprehension studies have observed significant syntactic priming without repeating a lexical item (such as the verb) between the prime and target sentence (e.g., Arai & Mazuka, 2014; Giavazzi et al., 2018; Kim et al., 2014; Lee et al., 2019; Pickering et al., 2013; Segaert et al., 2013; Tooley, 2020; Tooley & Bock, 2014; Ziegler & Snedeker, 2019). Results from these newer studies have begun to coalesce around a conception of syntactic priming in comprehension that, as in production, is non-transient and abstract, yet can be mediated by lexical factors.

For example, Pickering et al. (2013) tested structural interpretation of globally ambiguous, high/low attachment sentences such as "The waitress is prodding the clown with the umbrella." A comprehender must come to one of two readings to understand this type of sentence. Under a high attachment interpretation, the prepositional phrase "with the umbrella" refers to the verb and the sentence is comprehended to mean that the waitress is using the umbrella to do the prodding. The alternative low attachment interpretation means that the prepositional phrase refers to the clown, and the sentence is understood as the waitress prodding a clown who has an umbrella. Across two experiments, these authors manipulated the structural interpretation of a prime sentence by having participants choose one of two pictures depicting the sentence's meaning, with only one option including the correct object mentioned in the sentence. This picture showed the high attachment interpretation on high attachment prime trials and the low attachment interpretation on low attachment prime trials. The subsequent target sentence and picture-matching task served as the comprehension measure of structure, as both the high and low attachment interpretations were correctly pictured as options. Results revealed that the prime structure influenced target picture selection (structural interpretation) both when the verbs were repeated across prime and target as well as when they were different, though repeating the verb led to a larger priming effect (i.e., a lexical boost). These effects also persisted when a few (at least two) sentences intervened between the prime and target.

Pickering et al.'s (2013) results are quite similar to those observed in language production, and are also similar to production studies in that they use relative proportions of a forced-choice, structural outcome measure to gauge priming. It is important, therefore, to note that similar abstract priming effects have been observed for other dependent measures, such as reading times (Kim et al., 2014; Tooley, 2020; Tooley & Bock, 2014), anticipatory eye movements in a visual world paradigm (Arai & Mazuka, 2014; Ziegler & Snedeker, 2019), and the blood-oxygenation-level-dependent (BOLD) signal measured during fMRI (Segaert et al., 2013). Given that reading time measures are so commonly utilized in comprehension research, a good case in point comes from Tooley (2020). In this study, participants read reduced-relative clause target sentences (e.g., "The boy pushed by the girl made a sexist remark") that were preceded by prime sentences with either the same structure with the same initial verb, the same structure with a different initial verb, a different (locative) structure with the same initial verb,

or a different (main clause) structure with a different verb. Priming of target processing (indexed by shorter reading times on the critical regions of the target sentences) was observed only when prime and target sentence structure were the same. Additionally, this effect was more robust (occurred earlier and across more sentence regions) when the verb as well as the structure were the same across prime and target sentences, which is consistent with a lexical boost effect.

Beyond the monolingual adult population, abstract priming effects during comprehension have also been observed in young children (e.g., Arai & Mazuka, 2014) and second language learners (Nitschke et al., 2014; Weber & Indefrey, 2009; Wei et al., 2019). Notably, such structural priming studies (on language learners) are often undertaken as they offer a means of gauging how and when structural representations develop and change when learning a language. However, the findings from these studies extend current evidence for abstract priming during comprehension in important ways. Specifically, they provide evidence that abstract structural representations are integral to comprehension even in a language system that is less mature and/or where proficiency is continuing to develop.

For example, Arai and Mazuka (2014) investigated priming for the passive structure in Japanese (a verb-final language) using a visual-world paradigm. In the Japanese, active/passive alternation is made up of two noun phrases followed by a verb phrase. The agent appears in the first noun phrase in the active form and in the second noun phrase in the passive form. However, the structure cannot be determined until morphological information at the verb is encountered. Participants included groups of 5- and 6-year-old children and an adult comparison group. While listening to recordings of active or passive sentences and viewing a depiction of each sentence's meaning, participants' eye-movements were recorded. Prime sentences were either active or passive and their accompanying pictures contained two animate actors (such as a frog and a monkey) and showed one transitive event (such as the frog tapping the monkey). Target sentences included three actors involved in a chained event such that the middle actor was receiving an action from the first actor and initiating an action on the third actor. During the target trials, the middle entity was mentioned in the first noun phrase, and anticipatory looks to its patient suggested an active structural expectation, while looks to its agent indicated a passive structural expectation. After the target sentence, participants were asked a comprehension question that required them to state what happened to the middle character. The structure of their answers to these questions were coded as either active or passive. Despite target verbs always being different from their primes, and the verb occurring after both of the noun phrases, anticipatory eye-movements at the target (after the first noun) showed more of an agent preference after active primes. This result is consistent with an abstract priming effect for the Japanese passive structure. These effects were present in all three groups, though they were largest in adults and larger in 6-year-old than in 5-year-old children.

There is also evidence for abstract structural priming during comprehension in bilingual speakers (Nitschke et al., 2014; Wei et al., 2019). Nitschke et al. (2014) compared priming effects in speakers for whom German was their first language to proficient speakers of German who learned it as a second language (L2). Prime and target sentences were presented along with possible depictions of the sentences' meanings, and participants were tasked with choosing the picture that correctly matched each sentence's meaning. The stimuli for this study were globally ambiguous German relative clauses that could be interpreted as either subject-object-verb (SOV) or object-subject-verb (OSV) structures. Prime trials forced the structural choice of the less-preferred OSV structure, while target trials enabled either interpretation to be chosen. Over four experiments, both L1 and L2 speakers of German showed reliable priming for the OSV structure without any lexical overlap between primes and targets. Additionally, the size of the priming effect only differed between speaker groups when animacy also differed across prime and target trials. This implies that priming looks the same in proficient speakers, regardless of whether the language was learned as a first or second language.

Similarly, Wei et al. (2019) found syntactic priming effects during comprehension, which could be dissociated from lexical sources of facilitation, in Chinese L2 learners of English. Rather than using a dichotomous, picture-matching assessment of comprehension, this study used a self-paced reading paradigm that provided an online comprehension measure of difficult reduced-relative clause sentences. Though the tested structures were difficult because they were less common, structurally complex, and temporarily ambiguous, participants showed facilitated processing for the primed trials. Overall, we now have mounting evidence that abstract structural priming takes place during sentence comprehension across a variety of sentence types and language groups.

So far this review has focused on trial-to-trial priming effects, where priming is assessed at a target sentence that follows at least one structurally manipulated prime sentence. However, other studies have sought evidence of changes to abstract structural accessibility and/or representation during comprehension via investigating cumulative priming effects (e.g., Fine et al., 2013; Fine & Jaeger, 2016; Fraundorf & Jaeger, 2016; Myslín & Levy, 2016; Tooley & Traxler, 2018). In cumulative priming studies, changes in how a structure is processed or interpreted are assessed via online processing measures over multiple exposures to the "studied" structure. For example, Fine et al. (2013) investigated self-paced reading times for sentences that were

temporarily ambiguous between a main clause and the less-preferred relative clause structure. Though reading times were initially longer for the less-preferred structure, they gradually decreased within a single session, across multiple exposures to the structure. This supports the idea that rapid priming for the relative clause structure takes place and accumulates with exposure. In a follow-up experiment, Fine and colleagues also showed that the more preferred main verb structure could be made more difficult (relative to an unambiguous main verb structure) by first exposing participants to a block of only relative clause sentences. More recent studies have also found cumulative structural priming effects within a single comprehension session (Fine & Jaeger, 2016; Fraundorf & Jaeger, 2016; Myslín & Levy, 2016)[1] as well as across several sessions (Tooley & Traxler, 2018). These results highlight the malleability of structural representations and hint at the role implicit learning may play in shaping these representations over varying time spans. Implicit learning is discussed more thoroughly in the section The mechanistic debate continues, where competing mechanistic accounts are considered.

Structural priming differs across methodology more so than modality

The current body of literature strongly supports the idea that abstract syntactic/structural priming effects do occur during comprehension as in production. This is consistent with previous findings that show a comprehended prime affects a produced target to the same extent as a produced prime (Bock et al., 2007; Branigan et al., 2000; Lombardi & Potter, 1992; Potter & Lombardi, 1998), and supports theories that imply shared syntactic representations between comprehension and production modalities (Bresnan & Kaplan, 1984; Kempen et al., 2012; Pickering & Garrod, 2013; Sag & Wasow, 2011). However, one may still wonder whether abstract priming effects and the lexical boost differ systematically across language comprehension and production. This is particularly important to consider given that some observations of syntactic priming effects in comprehension are more lexically dependent (e.g., Arai et al., 2007; Arai et al., 2015; Carminati et al., 2008; Tooley et al., 2009) than complementary effects in production. Furthermore, the inherent difference in the order of sub-processes in comprehension relative to production make this possibility tenable. Specifically, production starts with an idea that can be conveyed using a particular syntactic structure, with words chosen to fit within that structure, whereas comprehension requires processing of individual words in order to build a structure and arrive at a particular meaning. Therefore, it is intuitively appealing to assume the impact of individual words may be greater during comprehension than production.

In contrast to this assumption, findings from recent studies that were designed to directly contrast structural priming effects in comprehension to those in production find equivalent effects across these modalities (e.g., Segaert et al., 2013; Tooley & Bock, 2014). For example, Segaert et al. (2013) used fMRI to assess brain responses during structural priming tasks that relied on either comprehension or production processes. They specifically focused on priming for the active/passive alternation where a sentence can be structured in either the active form (e.g., "The woman serves the man"), which has the agent in the subject role, or the passive form (e.g., "The man is served by the woman"), which has the patient in the subject role. Notably, this structure is widely used in production tasks, but much less studied in structural priming during comprehension. Though they observed a larger and more robust priming effect for the passive form in both modalities,[2] the priming effect in comprehension did not reliably differ from that in production. This result is important because it offers a direct comparison of structural priming across modality while relying on a shared measure of processing (i.e., BOLD signal). Most comparisons of priming across modality require comparing effects in an outcome measure (i.e., which structure was produced) to an online processing measure (such as reading or looking times). This is problematic as it has been found that outcome measures are often more sensitive to priming effects than reading time measures, even within the same modality (e.g., Segaert et al., 2016; Weber et al., 2019).

However, a behavioral comparison, where the nature of the dependent variable differed depending on the modality of prime and target sentences, also found parity for priming across comprehension and production. Specifically, Tooley and Bock (2014) endeavored to keep the task, structures, and participants constant in their comparison of structural priming during production to that in comprehension. To do this, they used structures that are common in both comprehension (main clause vs. relative clause) as well as production (prepositional object and double-object datives) studies. Furthermore, they utilized a less common priming task (slightly modified from Potter & Lombardi, 1998) that requires participants to view a very quick initial rapid serial visual presentation (RSVP) of a sentence, followed by a brief distractor task. This allows them to form a conceptual understanding of the meaning of the sentence, while leaving

[1] It is worth noting, however, that these effects have sometimes failed to replicate (Harrington Stack et al., 2018), and in-depth power analyses have suggested that they are much smaller than originally observed (see Prasad & Linzen, 2021).

[2] This may be due to the inverse frequency effect (Jaeger & Snider, 2013), which is explained in the following section on mechanistic accounts.

the memory for the wording of the sentence more malleable. This is followed by a prompt for the participant to either say the sentence they saw aloud (production prime trial) or do a self-paced read through the sentence (comprehension prime trial). Both trial types end by having the participant determine whether the sentence they said or read was different from the initial sentence they saw. This was followed by the target trials, which worked exactly the same way the prime trials did (and always matched the modality of the prime), but with a new target sentence. When standardized scores of the self-paced reading times of the target sentences were compared to standardized scores of the rate of producing the target sentence in the form that matched that of the prime, no reliable differences were observed.

Interestingly, in more fine-grained comparisons of priming effects across modality of particular structures, unanticipated differences emerged. These mostly related to internal sentence semantics that likely interacted with structural processing effects (i.e., reading "A girl microwaved her brother a casserole" resulted in local reading time slowdowns at "brother" as it is (initially) semantically an unsuitable, and rather gruesome, object of this verb). This anomaly lays bare the issues with using structures in both modalities that are intentionally chosen to be best suited to one – in this case, using ditransitive structures in comprehension, where they are traditionally used in production studies. Comprehension studies often use more complex structures, such as relative clauses, which, in turn, are difficult to use in production studies because eliciting the production of such structures is far from straightforward. All told, the results from Tooley and Bock (2014) highlight two important points about comparing structural priming effects across modality. One, that they are in general very similar and highly likely to rely on the same abstract structures and structural systems. And two, they can be influenced by specific methodological choices that affect the fine-grained processing of the sentence at multiple interacting levels of representation, not just the syntactic/structural level.

These conclusions are echoed by studies that focused on identifying methodological influences that possibly contribute to difficulties in observing structural priming effects during comprehension. Kim, Carbary, and Tanenhaus (2014) note that while production studies measure syntactic choice between two acceptable alternatives that can each convey the intended meaning of a sentence, comprehension studies often rely on real-time processing measures of ambiguous or complex sentences. Processing such stimuli sometimes requires readers to build and then discard a structure in order to arrive at the one intended structure (and meaning) of the sentence. These authors contend that this inherently involves additional processes that are affected by variables such as verb biases, lexical biases based on animacy and thematic role assignment, as well as structural biases. All together, these biases may mask structural priming effects that occur within the same channel of observation-reading time changes at a critical region. They tested this idea by conducting a syntactic priming study on ambiguous high versus low attachment structures, such as "The FBI agent noticed the mirror on the wall with the crack." They used a phrase-by-phrase reading task, but also included a forced-choice assessment of the meaning of the sentences (e.g., "What had the crack? (a) the wall, (b) the mirror"). This provided the researchers with both an online processing measure (reading times) and an outcome measure of the structural interpretation of the sentence (which is more akin to the measure of priming used in production studies). Critically, when modeling priming effects, they compared models that included item-level bias measures from stimuli norming data to those without these measures. They observed abstract structural priming effects in the reading time and outcome measures only when these bias measures were included in the models. These results highlight how lexical and structural biases may mask structural priming, as well as the difficulty of isolating structural priming effects with measures of comprehension.

Ziegler and Snedeker (2019) also investigated possible reasons why observing structural priming effects in comprehension can be more elusive. They used a visual world comprehension paradigm (with eye tracking) where ditransitive (direct object/prepositional object) prime and target pairs were embedded within a discourse. They included a discourse around their critical structures to test for priming of information structure (alongside syntactic structure), as well as to assess priming for structure in a context where there was less bias towards one message/structural alternative. This is in contrast to early visual world syntactic priming studies (i.e., Arai et al., 2007) where the predictability of the message was so high that it required little structural processing to arrive at the correct sentence interpretation. Specifically, the visual array included only the referents in the sentence (e.g., a pirate, a princess, and a necklace), and the sentences were very canonical (The pirate gives the princess the necklace/the necklace to the princess). Once the participant hears "the pirate gives" they can infer the meaning of the sentence based on the viewed referents and would not need to actively engage in structural processing that could lead to a priming effect. Consistent with this possibility, significant abstract structural priming effects were observed by Ziegler and Snedeker (while they were not in Arai et al.'s study). They also observed evidence of information structural priming in the early regions of the sentence, likely due to the inclusion of a discourse context. The effects observed here support the idea that abstract comprehension priming is more likely to develop in a context where comprehenders need to actively engage in structure-building processes to arrive at the correct message-level representation, as is the case during production. It also highlights the fact that other sources of facilitation occur

depending on the task context (such as critical regions being in a discourse or not).

This latter finding is noteworthy because it shows that other sources of overlap during comprehension priming studies can lead to additional facilitation when using structural priming paradigms. Consistent with this idea of layering of priming effects, Tooley et al. (2019) used eye tracking during reading to investigate influences on the lexical boost effect during comprehension, and what mechanisms likely contribute to this effect. They manipulated the degree of structural overlap between prime and target sentence pairs as well as the effects of thematic role and verb form overlap between primes and targets. They observed facilitated structural processing for difficult relative clause structures when the verb and structure were the same between primes and targets (i.e., a lexical boost/lexically mediated priming effect), as predicted. Interestingly, they also observed facilitated structural processing when thematic role assignment was shared across primes and targets, though this effect was smaller than the lexically mediated structural priming effect. Separate facilitation at the verb was also observed when the verb form was repeated across prime and target sentences. These additional priming effects, which can be observed for specific regions/measures in comprehension paradigms, are important to be aware of as they may help to explain why isolating a structural priming effect can be more difficult in comprehension than production. Specifically, the continuous measures of processing used as indicators of structural priming in comprehension also tap other on-going language processes, rather than just structural processes. This is in contrast to the outcome measures commonly used in production that assess structural choice after processing is complete and only for correctly completed trials. On the flip side, such findings also suggest that comprehension priming paradigms can be used to assess priming for other types of representations, at various stages of sentence processing.

Overall, it appears that many methodological differences across tasks, stimuli, and dependent variables can influence how structural priming effects manifest in studies of comprehension relative to those focused on production. These differences largely result in a more straightforward observation of abstract priming effects in production than in comprehension. However, attempts to account for and strip away the influences of these methodological differences have been largely fruitful. They converge on a view of abstract representation of structure (and facilitation of structure) that is unified across modality and observable with controlled manipulation.

The mechanistic debate continues

Understanding differences in observed priming effects across comprehension and production naturally leads to a discussion of the mechanism that causes structural priming. This was initially the case because differences in observed effects may have signaled differences in the way the underlying mechanism(s) behind these effects play out across modalities. This possibility is much less likely given more recent observations of the parity of structural priming across comprehension and production. However, it remains the case that accurate interpretation of structural priming effects relies on a causal understanding of its mechanisms. Though several mechanistic accounts have been proposed, strong consensus on the most likely mechanism(s) behind these effects is still lacking. In this section, I review several types of mechanistic accounts including empirical support for each, and discuss how theoretical explanation at the mechanistic level requires input from a broad range of effects.

Early observations of syntactic priming and the lexical boost in production studies spurred the first mechanistic account of these effects (Pickering & Branigan, 1998). Pickering and Branigan proposed a unitary mechanism to explain both abstract syntactic priming effects and the lexical boost, relying on earlier models of production processes (Levelt, 1992) and lemma representations (Roelofs, 1992, 1993) for a processing architecture. According to this account, structural nodes that represent particular phrase structures are represented as nodes that are linked to all verbs (also stored as nodes) that can participate in those structures. When a particular structural representation is used (either in production or comprehension), the node that represents it is activated. When planning/parsing a subsequent sentence, *residual activation* of the previously used structural node biases the language user toward reusing that same node and structure, producing a structural priming effect. When the verb that was present in the original structure is also present in the subsequent sentence, there is not only residual activation for the structural node, but also for the connection between the verb and structural node. This increase in residual activation (relative to when only the structural node retains activation) results in a larger structural priming effect, which is called the lexical boost.

Pickering and Branigan's Residual Activation account offers a compellingly parsimonious explanation of structural priming, as well as several testable assumptions. In particular, it assumes a tight representational coupling between structural information and word identity (at least for structural heads like verbs). It also assumes that the mechanism that produces priming is unlikely to be long-lived, given traditional understanding of representational activation (e.g., Roelofs, 1992). However, the lexical boost has been shown to decay with one or more sentences intervening between the prime and target (e.g., Hartsuiker et al., 2008), while abstract structural priming effects can persist over many intervening sentences (Bock & Griffin, 2000; Ferreira et al., 2008) and accumulate with exposure (Fine & Jaeger, 2016; Kaschak et al., 2011). These results

pose specific challenges for the residual activation account. First, if abstract priming effects and the lexical boost are caused by the same mechanism, why do their time courses appear to be so different? Secondly, why would abstract priming effects survive across so many intervening sentences if they are caused by lingering activation within the representational system? Lastly, how would multiple exposures compound these effects? To address these questions, Malhotra et al. (2008) reported a computational model of memory trace associations between structures and verbs using an unsupervised dynamic memory system. By using different parameters for the lexical-syntactic associations and structural representations, they were able to successfully reproduce the different latencies of abstract structural priming and the lexical boost as well as cumulative abstract priming effects. Thus, it is possible that a unitary "trailing activation" account can explain the observed pattern of structural priming effects, when instantiated within a memory system in a particular way.

However, this account is based solely on processing within the production system and it does not predict the inverse frequency effect – larger structural priming for a lower frequency structure or structural alternative (e.g., Hartsuiker & Westenberg, 2000; Jaeger & Snider, 2008; Scheepers, 2003). A competing account suggests that abstract structural priming is a form of implicit learning (see Seger, 1994, for a review of implicit learning) and the lexical boost is caused by reactivation of a short-term memory trace for the wording of the prime sentence (Bock & Griffin, 2000; Chang et al., 2000; Chang et al., 2006; Chang et al., 2012). Thus, structural priming occurs automatically as the structure-building process is facilitated and strengthened through repeated use. This mechanism was implemented as a computational model of structural prediction within the comprehension system, whose tunings then impact formulation of structure in the language production system (Chang et al., 2006, 2012). The learning occurs when feedback from the prediction system detects an error, causing a change in the weightings of the system. This error-driven learning of structure correctly predicts and simulates long-lived structural priming that is cumulative as well as the inverse frequency effect (due to a larger error signal for more surprising structures) (Jaeger & Snider, 2013).

Notably, this model also elegantly integrates structural assembly across language comprehension and production, which we have found to be consistent with the most recent experimental evidence. Furthermore, its predictions are consistent with recent developmental findings showing that immediate and cumulative priming take place in young children, and are likely caused by a single learning mechanism (Branigan & Messenger, 2016). Thus, this model has an advantage in that it can explain a broader range of language phenomena (other than structural priming). This is important because it offers a means of situating structural priming within the larger language processing landscape. Additionally, such a model provides new empirical predictions that can be tested across a variety of language contexts, such as different modalities, structures, and language groups.

The implicit learning model, as instantiated by Chang and colleagues, has failed to simulate a lexical boost effect (Chang et al., 2006). Yet, this is consistent with updated versions of the implicit learning account that specifically suggest the lexical boost is not caused by long-lived learning mechanism (see Chang et al., 2012). Instead, these accounts suggest that short-term memory binding between words in a sentence and the structure of that sentence produce the lexical boost (Chang et al., 2012; Rowland et al., 2012). This model thus integrates the dual memory systems in the brain (explicit short-term memory and long-term implicit memory) to explain the breadth of structural priming effects.

However, more recent research has called into question whether a short-term memory explanation of the lexical boost can adequately explain why the lexical boost is often restricted to repetition of the phrasal head such as the verb (Carminati et al., 2019; Cleland & Pickering, 2003; Mahowald et al., 2016), rather than for any content word in the sentence (but see Scheepers et al., 2017). Due to this shortcoming of the implicit learning account, some researchers have suggested a dual mechanism account, borrowing from explanations of both of the two previous accounts (e.g., Hartsuiker et al., 2008; Tooley & Traxler, 2010). This sort of account assumes that a long-lived mechanism like implicit learning is the likely cause of abstract priming effects, whereas a more short-lived mechanism, that relies on word and structure representations, such as residual activation, causes the lexical boost. This sort of account is supported by recent findings that abstract priming effects in comprehension accumulate with multiple exposures, but the size of the lexical boost remains stable across multiple exposures to a verb and structure pairing (Tooley & Traxler, 2018).

Reitter et al. (2011) created an ACT-R computational model of production processing in order to simulate well-known structural priming effects. This model operates as a hybrid between a learning explanation and a residual activation explanation of syntactic/structural priming effects. It assumed highly lexicalized representations of structure and modeled learning for structure (abstract priming effects) as changes in base-level activation for a given structure, making a previously produced structure more activated and thus more likely to be produced in the future. Due to the associations between structure and words in the model, the lexical boost occurs because of increased transient activation for recently used word and structure pairings. This model successfully simulates long-lived and cumulative abstract

priming effects, the inverse frequency effect, and the lexical boost. However, it remains to be seen whether the lexical boost simulated with this model would decay as quickly as has been found in previous studies (e.g., Hartsuiker et al., 2008). It also predicts that the lexical boost should occur for any repeated lexical material (when the structure is also repeated), which is inconsistent with the bulk of current findings showing repetition of a lexical head often necessary to produce a lexical boost (e.g., Carminati et al., 2019; Cleland & Pickering, 2003). Overall, a hybrid approach, like that of Reitter and colleagues, can better account for the range of observed structural priming effects. However, areas of improvement remain.

Understanding of structural priming effects at a mechanistic level is vital given how widely used these paradigms have become (see Branigan & Pickering, 2017). To truly understand what these findings mean, we need to know if they reflect learning, activation, or a little of each. Vice versa, to unravel the complex mystery of human structural representation and processing we need to correctly understand and interpret structural priming effects. One methodological takeaway from our current lack of mechanistic surety is not to assume that lexically mediated or "boosted" structural priming effects tell you something only about structure. This is a real issue as researchers sometimes opt to use repeated verbs and structure in their priming studies as a means of boosting their ability to detect an effect. The inherent assumption in this practice is that a lexical boost is the same thing as an abstract priming effect, only bigger and easier to find. At a mechanistic level, this can lead to a spurious interpretation of results, as these effects may reflect representation and processing that is lexical in nature rather than purely structural. This is especially important as the strengths of structural priming paradigms make them useful in other areas of language research, such as on thematic role assignment and processing (e.g., Chang et al., 2003; Tooley et al., 2019; Ziegler & Snedeker, 2018), conceptual representations (e.g., Slim et al., 2021), and prosody (e.g., Jungers & Hupp, 2009; Tooley et al., 2014, 2018).

Perhaps the lack of consensus in theoretical accounts of structural priming could be overcome by considering newer versions of exemplar models (e.g., Ambridge, 2020; Johns et al., 2020; Johns & Jones, 2015), rather than the currently accepted abstractionist models of language representation and use. Exemplar models differ radically from abstractionist models in that they store memory traces of specific instances, rather than an abstract representation generated from many instances. These models are able to generalize to new instances/experiences by comparing that new instance to all stored similar instances in memory. Thus, abstracted representations are never constructed and stored, rather the retrieval process of comparing across all stored exemplars to interpret new information simulates abstraction (see Jones, 2019, for a review). Exemplar models of semantic memory (Hintzman, 1986; Kwantes, 2005) have been developed and used to successfully simulate the semantic relatedness of information in memory without the need for a specific semantic memory store. More recently, this type of model has also been used to simulate human language acquisition characteristics (see Ambridge, 2020) and syntactic performance (Jamieson & Mewhort, 2005, 2011) purely based on coding, storing, and retrieving exemplars of previous language experiences.

Building on these previous models, Johns et al. (2020) created an exemplar model of language production (the instance production model or IPM) that was trained on 30,000,000 sentences from various online sources (such as Wikipedia articles). The IPM was able to produce well-formed sentences of three to seven words in length, with high accuracy (76–92% correct), in both English and French. They accomplished this by creating memory stores of each word and its relative position to all the other words in a given sentence. At retrieval, which involved providing a set of words from which to structure a sentence, the model ordered the words based on all previous orderings of those words (relative to the other words) stored in memory. The IPM model was also used to simulate structural priming effects using a modified version of Potter and Lombardi's (1998) structural priming task. In this new task, the wording of the prime sentence was coded with an ordering cue (as in the aforementioned simulation) as well as a context cue, which included only non-function words. After the prime, the model was given a two-option forced-choice task, where it had to choose between two alternative structural forms (i.e., active/passive and ditransitive DO/PO) of a sentence. The model successfully simulated structural priming effects for both types of structures. Additionally, it simulated persistent priming of structure across lags of one to five intervening sentences (with a gradual decrease in the magnitude of the effect as the number of intervening sentences increased), as well as a lexical boost effect. Lastly, the model reproduced Chang et al.'s (2003) finding of constituent order priming for spray-load structures that can be ordered as either theme-location or location-theme.

All told, the IPM model (Johns et al., 2020) handily reproduced a range of structural priming effects observed in language production tasks, all without any representation of structure at a higher level than sentence word ordering. It is worth noting, however, that the model could not be used for the most common structural priming tasks in production: picture description and sentence completion. This is because it lacked a way to simulate perceptual processing. Adding such a capability to the model would allow it the opportunity to simulate priming across a variety of tasks, as well as address more nuanced

questions of structural processing. One issue that would be informative to address using future models of this type is whether non-head lexical boost effects appear weaker than for structural heads (as has been observed by some), which cannot be explained by the current implicit learning account. Another important finding that this model could be used to (attempt to) simulate would be the shorter longevity of the lexical boost effect relative to abstract priming effects (e.g., Hartsuiker et al., 2008). Such a probe would be informative as to whether a single, exemplar representational account could produce the different time courses of abstract and lexically mediated priming effects, which have been interpreted as evidence of two separate priming mechanisms.

While the IPM focused on (a simplified version of) language production, other similar models have been used to simulate human sentence parsing and predictive processing during comprehension for behaviors such as reduced-relative clause processing (Johns & Jones, 2015). It may, therefore, be possible to integrate modality-specific models to create a model that simulates both production and comprehension processes. Ideally, this integrated model would be able to put exemplar-based accounts of structure (and structural priming) through rigorous comparisons to human data. For example, could it simulate equivalent structural priming in comprehension and production? Another issue future models would need to tackle is how to account for structural priming across different domains, such as those between mathematics, language, and music (Scheepers et al., 2011; Scheepers et al., 2019; Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016). It is hard to imagine how a model that lacks a way of abstracting structure would be able to account for domain-general structural priming effects without involved, cross-domain retrieval processes. The memory demands of exemplar models are one of their largest criticisms, and yet the memory demands would appear to be far greater if retrieval of all experiences from multiple domains had to be executed in order to interpret new information.

As it stands, the theoretical mechanistic debate pertaining to structural priming is at a bit of an impasse. The implicit learning account (e.g., Chang et al., 2012) appears most promising owing to its ability to account for the widest range of findings, its integration of comprehension and production processes, as well as its application to language acquisition and learning. However, its mechanistic explanation of the lexical boost remains rather under-specified and under-supported by recent findings (e.g., Carminati et al., 2019; Cleland & Pickering, 2003; Mahowald et al., 2016). This leaves the door open for other accounts to contribute to our understanding of the mechanisms that produce structural priming effects. Newer semantic memory accounts seem especially poised to shake up this stalemate. Regardless, future research needs to be explicitly devoted to adjudicating between competing accounts in order for theoretical knowledge on this matter to move forward.

Outstanding questions and future directions

Much has been learned about structural priming, representation, and processing during comprehension in the past few decades. Yet, there are still important questions left unanswered. As mentioned in the previous section, finding a consensus on a mechanistic account of these effects is paramount. Pertinent to the gap in mechanistic clarity is the general lack of synthesis between production and comprehension findings. Though less numerous than research on production, we now have a critical mass of papers that could be used as a basis for a meta-analysis of syntactic priming in comprehension, similar to what has been done in production (Mahowald et al., 2016). Better still would be a comprehensive meta-analysis of syntactic priming effects that includes both comprehension and production studies. This would be a good first step towards alleviating the "stay in your own lane" approach that seems predominant within each modality.

Papers that investigate structural priming in production largely ignore findings from comprehension, though the latter provides measures of structural processing that are absent in studies on production. For example, comprehension studies that use online processing measures provide the opportunity to measure processing during the prime structure as well as the target. Investigating processing of the prime sentence, and how that processing is related to later facilitation at the target sentence, offers a novel source of information that may provide new insights into how and why structural priming takes place. This synthesis could in turn pave the way for much-needed mechanistic and computational models of priming that better integrate the comprehension and production systems.

Our understanding of structural priming could also benefit from increased integration between investigations of trial-to-trial priming and cumulative priming effects. Studies on these two domains of priming focus on different sides of the same coin, yet rarely is there a meaningful bridge between them. To do this, there will likely need to be a consensus of what is meant by "short-lived" and "long-lived" structural priming effects. In a trial-to-trial priming study, any effect that survives across two or more intervening sentences is often considered long-lived. Yet, cumulative priming studies often operationalize long-lived

priming effects as those that can be observed after an entire testing session (usually an hour or more of exposure to a structure) or across different testing sessions. Heyselaar and Segaert (2022) make a temporal categorization that is helpful in this respect. They define trial-to-trial priming effects (the effect of a prime on an adjacent or near-adjacent target) as "short-term" priming, the effects of exposure to a structure over an individual experimental session as "cumulative" priming, and the effect of structural exposure during one session on a subsequent session as "long-term" priming. Having a consensus in operational definitions as they relate to the time course of structural priming will facilitate investigations into the temporal dynamics of these effects.

Long-term priming effects (as defined above) have thus far not been covered in this review because there are so few investigations of this phenomenon in comprehension. Tooley and Traxler (2018) offer one exception. In this study, participants had their eye movements tracked over five sessions where they read adjacent prime-target sentence pairs (trial-to-trial priming). The targets were (notoriously difficult) reduced-relative clauses, while the primes were either main clauses (alternative structure) or the same reduced-relative structure. Prime sentences always had the same verb as the target. Across the five sessions, gradual decreases in fixation times on the critical regions of the targets suggested long-term learning of the structure took place. Additionally, lexically boosted priming was observed within each session, and this effect did not vary in magnitude across sessions. Investigations such as this suggest that short-term and long-term priming can be assessed within the same study, which also enables researchers to assess the relationship between these effects. Similarly designed follow-up studies could be done to further probe the relationship between short-term and long-term abstract priming effects.

More research has been done on long-term priming effects in production (Heyselaar & Segaert, 2022; Kaschak, 2007; Kaschak et al., 2011, 2014) than comprehension, yet this literature is also rather limited. Kaschak (2007) found that participants will match their production of two structural alternatives (DO vs. PO, in this case) based on the relative proportions of these structures to which they were exposed a short time before. Though initially considered evidence for long-lived learning of structure, this effect is what we would now call a cumulative priming effect in production, as it is measured at the end of the exposure session. Importantly, such cumulative effects implicate the causal involvement of a learning mechanism(s) for structural priming.

This learning of structural biases has subsequently been shown to persist over the long term, through a week after exposure (Kaschak et al., 2011). Kaschak et al. (2014) investigated whether long-lived structural priming effects, gained through cumulative exposure to a structure in one task, would generalize to a new task a week later. While they replicated the finding from Kaschak et al. (2011) that the priming effect from one task persisted a week later when measured on that same task, they failed to find priming that generalized to a new task a week later. This is particularly intriguing because they also observed that cumulative exposure to a structure using one task (such as stem completion) led to priming for that structure on a new task (such as picture description) a short time after exposure. Together these results suggest that bias towards a particular structural alternative is more robust or generalizable immediately after exposure than a week later. This could implicate different memory mechanisms being involved for initial learning than for long-term learning effects. Consistent with these results, Heyselaar and Segaert (2022) showed that long-term priming for the passive structure persists at least a month in young adults, but only up through a week in healthy older adults. This discrepancy in the longevity of these effects can be explained by decreases in implicit learning abilities observed in older adults (Heyselaar et al., 2021).

These investigations beg further research to address important remaining questions about the nature and time course of structural priming effects. For example, at what point does a primed structural representation begin to indicate a meaningful change in one's structural biases? Also, how is the nature of a primed representation that persists across a few other structures different from that which persists across days or weeks of language use? These are questions that need to be addressed in order to scale up models of structural priming and representation to those of general structure learning and language change. Furthermore, they are questions that will require more research on language production as well as language comprehension. However, methodologies commonly used in comprehension studies that employ continuous processing measures (e.g., reading times, ERP, BOLD response) could provide better sensitivity for detecting changes in priming effects over time than the outcome measures used in production studies. This is therefore an area of research that could particularly benefit from additional research in comprehension.

Finally, more research should be devoted to understanding how the presence, magnitude, and longevity of structural priming effects change during initial language learning and throughout the lifespan. This line of inquiry is important as it can address whether the mechanism(s) that produce structural priming effects are related to the mechanism(s) involved in initial structural acquisition. Recent findings from young language learners seem to suggest that some proficiency with a given structure is required for structural priming to take place (e.g., Arai & Mazuka, 2014), which

may suggest these effects are separate from initial structural learning mechanisms. However, findings from bilingual learners who are acquiring a second language find that priming effects are not always modulated by proficiency (e.g., Hartsuiker et al., 2016). Future research that uses online measures of comprehension during learning of new structures in various learning contexts (i.e., young L1 learners, L2 learners, learners of artificial languages) could prove beneficial for addressing these critical outstanding questions.

Furthermore, studying aging language users offers opportunities to test novel predictions that could help adjudicate between competing mechanistic accounts. For example, the implicit learning account suggests that implicit learning causes abstract priming effects that are long-lived but that a short-term memory effect underlies the lexical boost. Since implicit and explicit memory abilities have different trajectories of age-related decline, this account would predict that performance on structural priming tasks would change with age, but at different timepoints for short-lived effects (e.g., the lexical boost) and long-lived effects (persistent abstract priming). Notably, this is also an area of research where language comprehension studies are considerably under-represented relative to language production studies. Additionally, it is an area of research where comprehension measures could offer a unique ability to track graded language processing changes over time (that outcome measures in production may be less sensitive to).

Summary and Conclusions Overall, the past decade or so has seen a needed uptick in the syntactic/structural priming research during comprehension. This newer body of findings has filled important gaps in the knowledge and theory surrounding these effects. Specifically, it suggests that priming effects during comprehension do not substantively differ from those in production. However, methodological differences in how these different modalities are studied likely affect how these effects manifest, and in turn, a researcher's ability to detect these effects. These findings reinforce the idea that structural representation and processing is largely shared accross modality. Unfortunately, newer findings in comprehension and production have been unable to advance the debate about whether structural priming effects are caused by a learning mechanism, an activation mechanism, a combination of these, or another mechanism entirely. Future research is needed to answer these and other important questions. This will likely require more synthesis of findings across different modalities, across different time scales of priming effects, and across different groups of language users, particularly emerging and aging language learners.

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