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Implicit learning of structure occurs in parallel with lexically-mediated syntactic priming effects in sentence comprehension

Kristen M. Tooley [a,*], Matthew J. Traxler [b]

[a] Texas State University, United States
[b] University of California, Davis, United States

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ABSTRACT

The aim of this study was to determine whether cumulative structural priming effects and trial-to-trial lexically-mediated priming effects are produced by the same mechanism in comprehension. Participants took part in a five-session eye tracking study where they read reduced-relative prime-target pairs with the same initial verb. Half of the verbs in these sentences were repeated across the five sessions and half were novel to each session. Total fixation times on the syntactically challenging parts of prime sentences decreased across sessions, suggesting participants implicitly learned the structure. Additional priming was also observed at the critical regions of the target sentences, and the magnitude of this effect did not change over the five sessions. These finding suggests long-lived adaptation to structure and short-lived lexically-mediated priming effects are caused by separate mechanisms in comprehension. A dual mechanism account of syntactic priming effects can best reconcile these results.

Syntactic priming, or structural persistence, refers to the facilitated processing of grammatical structure due to some previously processed information or structure. The representational and processing systems that generate syntactic priming effects during language comprehension and production remain an active area of inquiry (see Pickering & Ferreira, 2008 and Tooley & Traxler, 2010 for reviews of language production and comprehension, respectively). Some accounts attribute syntactic priming effects to short-lived enhancement of activity in memory systems that connect abstract word-level representations (lemmas) to syntactic structure representations (Malhotra, Pickering, Branigan, & Bednar, 2008; Pickering & Branigan, 1998). Other accounts attribute syntactic priming effects to learning mechanisms that may underlie long-lived changes in patterns of production (Chang, Dell, & Bock, 2006; Reitter, Keller, & Moore, 2011). This study focuses on the representational systems and processes that produce syntactic priming effects in *comprehension*. Specifically, we test whether the mechanism that produces long-lived changes in comprehenders' responses to syntactic structure information is also responsible for structural facilitation driven by lexical and structural overlap.

Syntactic priming in production

Syntactic priming is quite robust in language production (Bock, 1986; Bock & Griffin, 2000; Cleland & Pickering, 2003, 2006; Pickering & Branigan, 1998; and others), but has also been observed in several studies of language comprehension (Ledoux, Traxler, & Swaab, 2007; Pickering & Traxler, 2004; Arai, van Gompel, & Scheepers, 2007; Carminati, van Gompel, Scheepers, & Arai, 2008; Thothathiri & Snedeker, 2008a,b; Tooley, Traxler, & Swaab, 2009). Bock's (1986) original language production study asked participants to say sentences and then describe pictures of events, such as transfer events. Though the pictures could be described with either a double-object structure (e.g., "a rock star sold an undercover agent some cocaine") or prepositional object structure (e.g., "a rock star sold some cocaine to an undercover agent"), participants were more likely to use a structure, if they had just said a sentence with that particular structure. Importantly, this result was obtained when none of the content words were the same between the first sentence (the prime) and the sentence describing the picture (the target) (Bock, 1986). As such, this type of priming must not rely on any concrete lexical information, and is therefore considered to reflect priming of abstract syntactic structure.

Subsequent research has, however, revealed that lexical overlap between the prime and target sentences does increase the

* Corresponding author at: 601 University Drive, San Marcos, TX 78666, United States.
E-mail address: ktooley@txstate.edu (K.M. Tooley).

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magnitude of the priming effect (Pickering & Branigan, 1998). The increase in the size of the priming effect when there is a content word (usually a verb) shared between prime and target sentences has been termed the "lexical boost" (Pickering & Branigan, 1998). Both of these types of syntactic priming effects have been replicated many times over (see Pickering & Ferreira, 2008 for a review of abstract and lexically-boosted syntactic priming effects), in several different languages (e.g., Hartsuiker & Kolk, 1998; Scheepers, 2003; Shin & Christianson, 2012), across languages in bilingual speakers (e.g. Hartsuiker, Pickering, & Veltkamp, 2004; Loebell & Bock, 2003; Meijer & Fox Tree, 2003; Shin & Christianson, 2009), in real world corpus data (Gries, 2005), and in children as young as 3 years old (e.g. Branigan & McLean, 2016; Huttenlocher, Vasilyeva, & Shimpi, 2004).

A meta-analysis of syntactic priming effects in production found abstract syntactic priming effects to be long-lived and cumulative, and the lexical boost to be comparatively short-lived (Mahowald, James, Futrell, & Gibson, 2016). Furthermore, recent findings comparing these two types of syntactic priming effects across children and adults in a dialog game task also revealed persistent abstract priming effects and a quickly decaying lexical boost for both groups of participants (Branigan & McLean, 2016). This reinforces past findings (Hartsuiker, Bernolet, Schoonbaert, Speybroeck, & Vanderelst, 2008), and further suggests that different mechanisms produce abstract priming effects and the lexical boost in language production.

Mechanistic accounts of syntactic priming

Understanding the causes of syntactic priming effects has become one of several fruitful lines of follow-up research on this phenomenon. Pickering and Branigan (1998) suggested that a residual activation mechanism could explain both abstract priming effects and the lexical boost. Similar to lexical priming, this account suggests that residual activation for recently processed words and their linked structural representations make a particular structure more likely to be used in subsequent utterances. When the prime and target do not share a content word, residual activation of the structural representation of the prime alone produces priming for abstract structure. When the two sentences do share a content word, residual activation for both the representation of the word and its linked structural representation yield structural priming that is then greater in magnitude than when the residual activation only occurred for the structural representation. More residual activation produces larger priming effects, under this account.

Pickering and Branigan's (1998) account is parsimonious in that it can explain both abstract priming effects and the lexical boost with the same mechanism. However, residual activation for a cognitive representation would likely be relatively short-lived. Thus, a logical prediction under this account is that syntactic priming effects should also be short-lived, meaning that the effect that a prime has on a target should dramatically decrease (or even be eliminated) when there are structurally unrelated sentences intervening between prime and target sentences. This prediction is contradicted by experimental evidence that abstract priming effects in language production persist across several (up to ten) intervening sentences without any meaningful decrease in magnitude (Bock & Griffin, 2000). The residual activation account is muddied further by additional findings that, while abstract effects appear to be long-lived, the lexical boost can decay with any intervening material (Branigan & McLean, 2016; Hartsuiker et al., 2008). These findings are easier to reconcile with an account that proposes different mechanistic causes of abstract priming effects and lexically-boosted priming effects (but see Malhotra et al., 2008 for a dynamical systems explanation of an activation account that could be consistent with different longevities for abstract effects and the lexical boost).

Bock and Griffin (2000) and Chang et al. (2006) suggest that the abstract priming effects in production are likely due to long-term implicit learning effects, rather than short-term activation changes. Chang and colleagues instantiated this view in a computational model whereby input (from the comprehension system) helps to establish syntactic regularities, and feedback from productions (output) allow for adaptive changes in those regularities. Implicit learning occurs when repeated exposure to a particular sequence or structure changes the strengths of connections between the elements of that sequence or structure (Seger, 1994). The nature of implicit learning for syntactic structure is suggested to be error-based, in that a mismatch between predicted and processed structure yields greater learning through greater adjustments of weightings in the representational system (see Fine and Jaeger, 2013 and Jaeger & Snider, 2013). Such an account predicts cumulative abstract priming effects and larger priming effects for less frequent structures (the inverse frequency effect), both of which have been observed in recent studies of comprehension (Fine, Jaeger, Farmer, & Qian, 2013; Fraundorf & Jaeger, 2016) and production (Kaschak, Kutta, & Jones, 2011).

Under the implicit learning account proposed by Bock and Griffin (2000) and by Chang et al. (2006), weightings between representations of individual words and the structures in which they participate are slow to change. This implies that this learning mechanism is not the cause of the lexical boost, as it manifests much earlier than this mechanism could produce. Instead, learning of verb-and-structure pairings would result in gradual weighting changes that would manifest as structural biases for individual verbs based on the overall distribution of structures in which they have been experienced. The cause of the lexical boost is suggested to be explicit memory for the wording of the prime sentence, which biases word order processing of the target (Bock & Griffin, 2000; Chang, Janciauskas, & Fitz, 2012; Chang et al., 2006).

A memory-based account has also been proposed to explain abstract priming effects and the lexical boost, with different memory-based retrieval mechanisms producing each of these effects (Reitter et al., 2011). Reitter, Keller, and Moore suggested that abstract priming effects are driven by a learning mechanism that affects base-level activation for syntactic chunks in long-term memory. Recently retrieved syntactic chunks have higher base-level activation, making them easier to retrieve when planning future utterances. This activation change is assumed to be somewhat slow to decay and accumulates with exposure, which can account for long-lived abstract priming effects. The lexical boost is suggested to be the product of spreading activation for recent lexical information in working memory to syntactic chunk information in long-term memory. Information in working memory is ephemeral in nature, and so this mechanism accurately predicts a short-lived lexical boost. By implementing these mechanisms in an ACT-R computational model, Reitter and colleagues were able to simulate many behavioral findings in production, such as the inverse frequency effect and cumulative priming effects.

Syntactic priming in comprehension

Syntactic priming has been mostly investigated in language production paradigms. However, many complementary studies on comprehension have emerged in the last decade (see Tooley & Traxler, 2010 for a review). Initially, findings from trial-to-trial priming studies noted an asymmetry between comprehension and production whereby lexically-mediated priming effects were widely observed in the absence of abstract priming effects (Arai