



Comprehension priming as rational expectation for repetition: Evidence from syntactic processing



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ARTICLE INFO

Article history:

Received 23 June 2013

Revised 7 October 2015

Accepted 31 October 2015

Available online 19 November 2015

Keywords:

Psycholinguistics

Priming

Expectation

Rational analysis

Syntax

Probabilistic models of cognition

ABSTRACT

Why do comprehenders process repeated stimuli more rapidly than novel stimuli? We consider an *adaptive* explanation for why such facilitation may be beneficial: priming is a consequence of *expectation for repetition* due to rational adaptation to the environment. If occurrences of a stimulus cluster in time, given one occurrence it is rational to expect a second occurrence closely following. Leveraging such knowledge may be particularly useful in online processing of language, where pervasive clustering may help comprehenders negotiate the considerable challenge of continual expectation update at multiple levels of linguistic structure and environmental variability. We test this account in the domain of structural priming in syntax, making use of the sentential complement–direct object (SC–DO) ambiguity. We first show that sentences containing SC continuations cluster in natural language, motivating an expectation for repetition of this structure. Second, we show that comprehenders are indeed sensitive to the syntactic clustering properties of their current environment. In a series of between-groups self-paced reading studies, we find that participants who are exposed to clusters of SC sentences subsequently process repetitions of SC structure more rapidly than participants who are exposed to the same number of SCs spaced in time, and attribute the difference to the learned degree of expectation for repetition. We model this behavior through Bayesian belief update, showing that (the optimal degree of) sensitivity to clustering properties of syntactic structures is indeed learnable through experience. Comprehension priming effects are thus consistent with rational expectation for repetition based on adaptation to the linguistic environment.

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1. Introduction

Repetition facilitates processing. Human comprehenders process words, pictures, faces, and everyday environmental sounds more rapidly when these stimuli are immediate repetitions than when they are novel (for review, see [Bigand, Tillmann, Poulin-Charronnat, & Mandlerier, 2005](#)). Why do comprehenders remain prepared to process a stimulus after its first presentation? We consider an *adaptive*, computational-level account of why such facilitation may be beneficial: priming is a consequence of *expectation for repetition* due to rational adaptation to the environment ([Anderson, 1990; Marr, 1982](#)). Clustering of repeated events in time, rather than uniform spacing, is pervasive in human dynamics, from economic transactions to instant messages to the occurrence of words in newspaper headlines over time ([Anderson & Schooler, 1991; Vazquez et al., 2006](#)). Given such clustering, it is rational for comprehenders to increase their expectations for

another instance of an event closely following a first occurrence. Where possible, then, it would be adaptive for comprehenders to learn and deploy knowledge of the clustering properties of the current environment, coming to more strongly expect repetitions in environments where stimuli cluster than in those where they do not.

Leveraging such knowledge may be particularly useful in the domain of language comprehension. Online linguistic processing is an incredibly complex cognitive feat, requiring comprehenders to continually update expectations at multiple levels of structure while negotiating considerable environmental variability. It is also the case that language is the naturalistic clustering environment par excellence, wherein tokens of the same type often occur in closer succession than predicted by chance. Such structure in language, if comprehenders are sensitive to it, may provide invaluable cues in forming accurate expectations of upcoming input, allowing for efficient language comprehension.

Here we present the first test of this account in online language processing, in the domain of sentence processing. It is known that processing of a sentence is faster if its syntactic structure is

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repeated from a preceding sentence. Consider the well-studied sentential complement–direct object (SC–DO) ambiguity (Garnsey, Pearlmutter, Myers, & Lotocky, 1997)¹:

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- (1) Her friend whispered the solution
 (a) was to dispose *Sentential complement (SC)*
 of the evidence.
 (b) very quietly in her ear. *Direct object (DO)*
-

In this context, verbs such as *whispered* in (1) may subcategorize for one of two syntactic structures, sentential complements as in (a) or direct objects as in (b). Even controlling for factors such as verb repetition and subcategorization bias, comprehenders who have recently encountered the SC structure process subsequent SCs more rapidly (e.g. Fine, Qian, Jaeger, & Jacobs, 2010). If this facilitation is due to an adaptive, rational expectation for repetition of SC structures across sentences, it should be most robust in environments in which SC sentences are very likely to follow SC sentences (regardless of the total number of SCs in the environment). In this paper, we show for the first time that manipulating the clustering properties of the environment indeed affects processing of syntactic structures, such that comprehenders in an environment in which SC sentences cluster process repeated SCs more rapidly than comprehenders in anti-clustering environments. We also present a Bayesian belief-updating model that shows that the relative importance of clustering properties in the environment, as well as the particular shape of the current clustering properties, are indeed learnable through experience. These results support a rational expectation adaptation account in which facilitation of repeated structure is due to adaptation to general environmental experience.

The paper is structured as follows. Section 2 reviews evidence for structural priming in syntactic processing and surveys existing accounts of the phenomenon. Section 3 proposes a rational expectation-based account of these effects. Section 4 presents a corpus study showing that SC sentences indeed cluster in natural language, motivating such an expectation for repetition. Sections 5 and 6 show that comprehenders are indeed sensitive to the clustering properties of the environment through a series of self-paced reading experiments in which clustered and anti-clustered experience had differential effects on the processing of repeated SC structure. Section 7 presents a Bayesian belief-updating model of this adaptation that shows that sensitivity to clustering properties is learnable through experience. Section 8 discusses theoretical implications of an expectation-based account of priming, and Section 9 concludes.

2. Structural priming in syntax comprehension

2.1. Experimental evidence

Repeated syntactic structure facilitates comprehension. Sentences that repeat structure from previously-comprehended sentences are read faster, elicit smaller changes in brain activity, and are rated as more grammatical than sentences that do not repeat structure. For example, reduced relatives are read faster following a reduced relative prime than when following a main verb prime (Pickering & Traxler, 2004; Traxler & Tooley, 2008). These kinds of effects have been experimentally shown to persist for up to sev-

eral weeks (e.g. Wells, Christiansen, Race, Acheson, & Macdonald, 2009), may be elicited with as few as just one prime sentence (e.g. Fine et al., 2010), and are usually not dependent on repetition of particular verbs (Thothathiri & Snedeker, 2008, although this does usually result in a *lexical boost* of priming). Further, interpretations of ambiguous structures are influenced by recently comprehended structures: for example, comprehenders are more likely to choose high-attached interpretations of prepositional phrases after reading a prime expression with a high-attached interpretation, or even after seeing mathematical expressions with analogous parenthetical groupings, suggesting domain generality of structural priming (Branigan, Pickering, & McLean, 2005; Scheepers et al., 2011). The now relatively extensive literature on structural priming in comprehension is reviewed in Pickering and Ferreira (2008) and Tooley and Traxler (2010).

2.2. Theoretical accounts of structural priming

Most accounts of structural priming are cast at Marr's (1982) algorithmic level of analysis, falling into two broad classes: *residual activation* and *implicit learning*. Residual activation accounts of priming, ported from production research to comprehension research, hold that accessing a particular syntactic structure increases that structure's mental activation level for a brief period but rapidly decays, leading to speeded processing of subsequent tokens of the structure (e.g. Pickering & Branigan, 1998). Implicit learning accounts, on the other hand, stipulate that processing a structure leads to unconscious learning of its associated representation, and the amount of exposure determines the strength of learning and ease of subsequent processing (Bock & Griffin, 2000; Chang, Dell, & Bock, 2006). *Dual mechanism* accounts argue that residual activation explains short-term, lexically driven priming, while implicit learning explains longer term, lexically independent priming (Hartsuiker, Beronlet, Schoonbaert, Speybroeck, & Vanderelst, 2008; Reitter, Keller, & Moore, 2011).

Building on implicit learning accounts at the computational level of analysis are *expectation adaptation* accounts, seeking to explain the adaptive benefits of these behaviors. Starting with the premise that context-specific comprehender expectations for upcoming syntactic structures affect processing (the *SURPRISAL* theory; Hale, 2001; Jurafsky, 1996; Levy, 2008), and given the objective of easing processing and allocating resources efficiently, a rational behavior is for these expectations to converge on the statistics of the environment (argued in detail below and in Anderson (1990) and Fine, Jaeger, Farmer, & Qian (2013)). Recent evidence suggests that these expectations can be modulated in the same ways that classic structural priming has been seen to operate. Fine et al. (2013) show that given a verb that may occur as a main verb or as the verb in a relative clause, comprehender expectations initially reflect their prior experience that main verbs are the more frequent continuation, but the more relative clause continuations recently experienced, the more strongly comprehenders come to expect relative clauses. Similar results were obtained by Kaschak and Glenberg (2004), where processing of a novel syntactic construction (*needs done*) sped up with additional exposures over a single experimental session; by Wells et al. (2009), where object relative clauses became easier with more exposure over several weeks; by Fine et al. (2010), where sentential complements (SCs) were processed faster the more they had occurred in recent experience; by Farmer, Fine, and Jaeger (2011), where comprehenders rapidly learned environment-specific verb biases for syntactic continuations; and by Kamide (2012), where comprehenders learned syntactic preferences of individual speakers. Rapid expectation adaptation has also been demonstrated in speech perception (Kleinschmidt & Jaeger, 2011; Kraljic, Samuel, & Brennan, 2008), prosody (Kurumada, Brown, & Tanenhaus, 2012), and pragmatics

¹ Although our case study involves a syntactic ambiguity, our theoretical arguments do not implicate ambiguity resolution as a specialized process. We take a surprisal-based view of syntactic processing, in which structural ambiguity *per se* does not influence processing difficulty, and instead is relevant only insofar as its effect on conditional word probabilities (Levy, 2008, 2013). Thus, in principle, our investigation of syntactic repetition applies to any arbitrary syntactic structure, whether or not it participates in an ambiguity.

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