Syntactic priming in language comprehension allows linguistic expectations to converge on the statistics of the input

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Abstract

Human language is characterized by variability in that the way in which language is used varies depending, for example, on facts about the identity of the speaker or author, the social context, and surrounding linguistic material. Variability poses formidable challenges to the systems underlying language comprehension, which are known to exploit statistical contingencies in the input to overcome the inherent noisiness of perception; nevertheless, we seem to comprehend language with apparent ease. How is this possible? Here we argue that we are able to comprehend language efficiently in part by continuously *adapting* to the statistics of novel linguistic situations. We argue further that adaptation specifically allows comprehenders' expectations to converge towards the actual statistics of the linguistic input. Concretely, we show that readers can adjust their linguistic expectations in light of recent experience such that (a) previously difficult structures become easier to process, and, even more strikingly, (b) previously easy to process structures come to incur a processing cost.

Keywords: Sentence processing; experience-based language processing; parsing; reading; learning; adaptation; priming

Introduction

Human language is *variable* in the sense that the way in which language is used varies across situations according to, for example, the social context, the surrounding linguistic material, and various facts about the identity of the speaker or author. Variability in this sense pervades our linguistic experience, and has been observed at virtually every level of linguistic representation.

Despite the extent to which language use varies, communication is typically successful. That is, even when faced with novel speakers or accents, we seem to be able to quickly and accurately infer the messages intended by our interlocutors.

Our apparent facility with language is particularly remarkable considering the extent to which *linguistic experience* has been demonstrated to play a role in language processing. Experience-based accounts of language processing hold that comprehenders generate expectations—about the probability of observing particular sounds, words, sentence structures, etc.—during online language processing, and that these expectations are informed by and reflect the statistics of previous linguistic experience. By generating expectations that reflect the actual distribution of events in the environment, comprehenders should, in principle, be able to reduce the average prediction error experienced during online processing, and thus process language efficiently. But if the distribution of words or sentence structures varies according to individual speakers, dialects, etc., then, at first blush, it is no longer clear that generating online linguistic expectations that reflect aggregate statistics over previous experience would be advantageous to the comprehender. How do we comprehend language as well as we do despite variability in the linguistic signal?

Here we present evidence that comprehenders are able to rapidly *adapt to* or *implicitly learn* the statistics of novel linguistic situations, focusing specifically on sentence comprehension ("parsing"). We argue that syntactic adaptation allows comprehenders' expectations about the statistics of the input to converge towards the actual statistics, providing an explanation for why experience-based processing is advantageous despite the variability present in the statistics of the signal. Our experiments build on and attempt to synthesize insights from three lines of research that have till now proceeded largely in parallel: (1) experience-based language processing (e.g., MacDonald, Pearlmutter, & Seidenberg, 1994), (2) syntactic priming (e.g., Traxler, 2008), and (3) research exploring the link between online processing and implicit learning (e.g., Misyak & Christiansen, 2012; Wells, Christiansen, Race, Acheson, & MacDonald, 2009).

To test our hypothesis, we exploit a well-known temporary syntactic ambiguity that provides a window onto comprehenders' expectations, illustrated in (1).

1. The experienced soldiers…
   a. …warned about the dangers **before the midnight** raid.
   b. …spoke about the dangers **before the midnight** raid.
   c. …warned about the dangers **conducted the midnight** raid.
   d. …who were warned about the dangers **conducted the midnight** raid.

Verbs like *warned* give rise to temporary ambiguities since they may occur both as the main verb (MV) of a

sentence ((1a)) or as the verb in a relative clause (RC; (1c)). Sentences (1a) and (1c) can be disambiguated toward the RC reading at *conducted*, like in (1c). By contrast, (1b) is unambiguously an MV structure because *spoke* is unambiguously a past tense matrix verb; (1d) is unambiguously an RC because of the relativizer *who*, which serves as an early disambiguating cue. Sentences like (1c) consistently elicit what are known as ambiguity or garden-path effects: reading times (RTs) in the disambiguating region (in bold) spike when the ambiguity is resolved towards the relative clause interpretation (1c), compared to unambiguous RCs (1d). No such ambiguity effect is found for ambiguous compared to unambiguous MVs. Experienced-based accounts predict the garden-path effect because verbs like *warned* are overwhelmingly more likely to occur with MVs than RCs in subjects' previous experience, as evidenced in corpora of written and spoken language.

Given that this frequency difference has a reliable correlate in human behavior, we can take advantage of the MV-RC ambiguity to explore syntactic adaptation. We provide subjects with experience with written language in which the environment-specific syntactic statistics differ sharply from subjects' previous experience with language. If subjects are adapting to the statistics of the input, as we propose, then the manner in which subjects process these structures should change over the course of the experiment. Specifically, if exposed to locally stationary syntactic distributions—i.e., distributions whose parameters remain fixed within the environment—comprehenders' syntactic expectations should *converge* towards the statistics of the environment. In Experiment 1, we find evidence for rapid, incremental, and cumulative syntactic adaptation: over the course of an experiment where RCs are many times more likely than in subjects' previous experience, the ambiguity effect for these structures continuously decreases until it disappears. Experiment 2 goes a step further. There, we reason that if subjects indeed adapt their expectations to converge towards the statistics of the input, then as subjects come to assign a *higher* subjective probability to RCs, they should commensurately come to assign a *lower* subjective probability to MVs. Since MVs by hypothesis compete with RCs for probability mass (in the type of garden path sentences we investigate) it should be possible to make MVs sufficiently unlikely that this structure would actually *come to incur a processing cost*. This is what we find.

Experiment 1

In Experiment 1 we ask whether comprehenders can rapidly adjust their syntactic expectations in response to the statistics of a novel linguistic situation (i.e., in response to the statistics of the experiment). We expose subjects to 40 ambiguous and unambiguous RCs, as in (1c) and (1d). Because RCs are infrequent structures, we predict that subjects will display an initially high processing cost for ambiguous relative to unambiguous RCs (i.e., a large ambiguity effect), but as the experiment progresses, and evidence accumulates that RCs are highly probable within the context of the experiment, we predict that the ambiguity effect should diminish.

Subjects

80 subjects were recruited via Amazon's Mechanical Turk platform. Only subjects with US IP addresses were allowed to participate. Additionally, instructions clearly indicated that subjects were required to be native speakers of English, and only subjects with at least a 95% approval rating from previous jobs were included.

Materials

Critical items were constructed from sentence pairs like (1c) and (1d). Eight different verbs giving rise to the MV/RC ambiguity (*watched*, *washed*, *taught*, *served*, *called*, *warned*, *dropped*, *pushed*) were repeated 5 times to yield 40 critical items (only the verbs were repeated; the remainder of the sentences differed between items). Ambiguity was counter-balanced across two experimental lists. In addition, each list contained the same 80 fillers. Filler sentences featured a variety of syntactic structures and, crucially, did not include verbs that give rise to the MV/RC ambiguity (e.g., *All the undergraduates in the class had trouble keeping up*; *The foreign delegates arrived at the embassy surrounded by security guards*). Both lists presented stimuli in the same, pseudo-randomized order with 1-3 fillers between each critical item. Two additional lists were created in which the order of items was reversed, yielding a total of 4 orders.

Procedure

Stimuli were presented in a self-paced moving window display. At the beginning of each trial, the sentence appeared on the screen with all non-space characters replaced by a dash. Subjects pressed the space bar using their dominant hand to view each consecutive word in the sentence. Durations between space bar presses were recorded. At each press of the space bar, the currently viewed word reverted to dashes as the next word was converted to letters. A yes/no comprehension question followed all experimental and filler sentences, with the correct answer to half of all comprehension questions being "yes".

Results

RTs less than 100ms or greater than 2000ms were excluded before computing length-corrected RTs (i.e., RTs with the effect of word length removed) following a procedure similar to the one described in Ferreira and Clifton (1986).

Length-corrected RTs during the disambiguating region (in bold in (1) above) were regressed, using mixed effects regression, onto the full factorial design (i.e., all main effects and interactions) of ambiguity (ambiguous vs. unambiguous) and item order (coded 1-40 and centered). Item order captures the number of RCs observed at a given point in the experiment. Additionally, we included a main

effect of log-transformed stimulus order, which provides an index of how many trials (including both critical items and fillers) have been read at a given point in the experiment. Stimulus order captures the effect of "task adaptation", i.e., general speed-up effects, which can be rather strong in self-paced reading experiments (all results reported below hold with or without this predictor, and regardless of whether it is log-transformed). For this and all other analyses reported in this paper, we included the maximal random effects structure justified by the data (Jaeger, 2009).

We replicated the significant main effect of ambiguity found in previous studies: RTs in the disambiguating region were greater for ambiguous relative to unambiguous sentences (β=19, p<.001). Also replicating previous work, we found a significant main effect of log stimulus order (β=-39, p<.05) and a marginally significant main effect of item order (β=-2, p=.09). That is, subjects read stimuli increasingly faster as the experiment progressed, presumably reflecting task adaptation effect (getting used to the self-paced reading paradigm, Fine, Qian, Jaeger, & Jacobs, 2010) Crucially, there was a significant two-way interaction between ambiguity and item order: the processing cost incurred by ambiguous RCs—the ambiguity effect—significantly diminished as experience with RCs accumulated (β=-1, p<.05). In Figure 1, we visualize this interaction by plotting mean length-corrected RTs for ambiguous and unambiguous sentences across four bins of item order, and by plotting the ambiguity effect at all 40 points in the course of the experiment. Both the ambiguity effect and its interaction with item order were observed only in the disambiguating region. The effect of stimulus order was significant or marginally significant in all sentence regions.

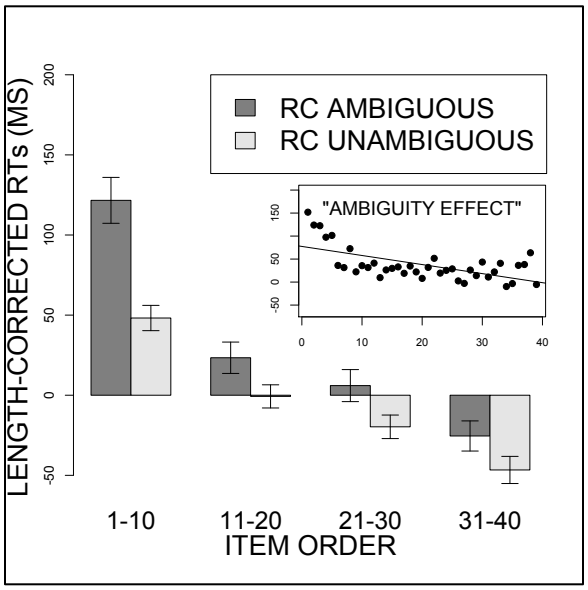

Figure 1: Mean length-corrected RTs during the disambiguating region for ambiguous and unambiguous RCs across four bins of item order in Experiment 1, with embedded visualization of the change in ambiguity effect across the course of the experiment. Error bars give 95% confidence intervals on the mean.

Discussion

Experiment 1 demonstrates that comprehenders are capable of rapidly, incrementally, and cumulatively adapting to the statistics of a novel linguistic environment, even after controlling for the effect of practice or task adaptation.

In the Introduction we articulated a conceptualization of syntactic adaptation according to which subjects continuously adjust their expectations such that their expectations about the linguistic environment converge towards the statistics of the linguistic environment. The results of Experiment 1 are compatible with such an interpretation, but do not rule out other plausible ones. For example, it is possible that the results of Experiment 1 are driven by boosts in the base-level activation of the RC structure, but that this happens without specific reference to the statistics of the input (Pickering & Garrod, 2004), or that adaptation occurs by virtue of episodic memory for the repeatedly encountered structure, which similarly would not need to make reference to the statistics of the environment (Kaschak & Glenberg, 2004). In Experiment 2, we present a more direct test of the prediction that comprehenders adjust their expectations to converge towards the statistics of the input.

Experiment 2

Experiment 2 exploits the same temporary ambiguity between MVs and RCs used in Experiment 1. However, unlike in Experiment 1, we expose subjects to both RCs and MVs. As we mentioned above, the ambiguity effect observed for sentences like (1) is driven by large differences in the probabilities of the two structures: upon observing the string *The experienced soldiers warned…*, subjects have a stronger a priori expectation for an MV interpretation relative to the RC interpretation. In other words, MVs and RCs *compete for probability mass*: MVs receive a high subjective probability at the expense of RCs. Therefore, if the results of Experiment 1 are driven by convergence towards the statistics of the input, then as subjects come to find RCs more probable, they should also, in turn, find MVs *less* probable. This effect should be observable in a decreased ambiguity effect for RCs and an increased ambiguity effect for MVs as the experiment progresses.

Experiment 2 employs a between-subject block design to test this prediction. In this experiment, subjects were assigned to one of two groups, which we will call the Filler-First and the RC-First groups. Subjects were exposed to three blocks of sentences. The composition of the materials in each block, for each group, is shown in Table 1.

Table 1: Summary of the between-subject, block design of Experiment 2.

Group	Block 1	Block 2	Block 3
RC-First (n=40)	16 RCs (8 ambiguous)	10 RCs (5 ambiguous) + 20 fillers	10 MVs (5 ambiguous) + 15 fillers
Filler-First (n=40)	16 fillers	10 RCs (5 ambiguous) + 20 fillers	10 MVs (5 ambiguous) + 15 fillers

We conducted Experiment 2 with three specific predictions in mind. We predict (1) that the ambiguity effect for RCs will be diminished from block 1 to block 2 for the RC-first group. This would conceptually replicate Experiment 1. We further predict (2) that the ambiguity effect for RCs during block 2 for the Filler-First group will be greater than that of the RC-first group. If the effects observed in Experiment 1 are due to task adaptation or fatigue, then the ambiguity effect for RCs in Block 2 should be the same for both the Filler-First and the RC-First group. In other words, reading a given number of sentences should have the same effect on reading times regardless of the content of those sentences. Finally, and most crucially, we predict (3) that the ambiguity effect for MVs should increase as experience with RCs increases. If adaptation is a matter of subjects' expectations converging on the statistics of the input, then as the ambiguity effect for RCs decreases, the ambiguity effect for MVs should increase. Thus, we predict a greater ambiguity effect for MVs in block 3 for the RC-First group (where subjects have encountered more RCs by the time they reach block 3) relative to the Filler-First group.

Subjects

80 subjects were recruited from the University of Rochester community. Informed consent was obtained from all subjects according to the University's scientific research ethics policies. Subjects received $10 for their participation.

Materials

Subjects read a total of 71 sentences over 3 blocks (as outlined in Table 1). RC and MV sentences were created that followed the same template as the critical items from Experiment 1. Two experimental lists were constructed for each group that counter-balanced the conditions (ambiguous vs. unambiguous) for the sentence type (MV or RC) used within each block, totaling four lists. It is important to note that the block structure of the experiment was entirely implicit. From the perspective of the subjects, they simply read 71 sentences without breaks.

Procedure

The same procedure as in Experiment 1.

Results

RTs less than 100ms or greater than 2000ms were excluded before computing length-corrected RTs, as in Experiment 1. We tested three predictions that follow from the hypothesis that readers adapt to the local statistics of the linguistic environment, enumerated above.

Prediction 1 (does the ambiguity effect in the RC-First group diminish from block 1 to block 2?): We regressed length-corrected RTs during the disambiguating region (underlined in (1)) of sentences read during blocks 1 and 2 in the RC-First group onto ambiguity (ambiguous vs. unambiguous), block (block 1 vs. block 2), and the two-way interaction between these predictors. There was a significant effect of ambiguity (β=65, p<.05): ambiguous RCs were read more slowly than unambiguous RCs. There was also a significant main effect of block (β=-72, p<.05): subjects read faster during the second block relative to the first block. Finally, the interaction between these two variables, capturing the change in the ambiguity effect from block 1 to block 2, was in the predicted direction and trended towards but did not reach significance (β=18, p=.2). It is likely that the binned comparison of reading times across blocks 1 and 2, combined with fewer observations than in Experiment 1, provides less power than the treatment of RCs as a continuous variable in Experiment 1. To address this, we took data from blocks 1 and 2 for the RC-First group and submitted it to the same analysis reported for Experiment 1. We examined length-corrected RTs during the disambiguating region using the same analysis as in Experiment 1. All critical effects from Experiment 1 were replicated including, importantly, a two-way interaction between ambiguity and item order (β=2, p<.05, after Bonferroni correction for multiple comparisons), replicating Experiment 1.

Prediction 2 (is the ambiguity effect in block 2 greater for the RC-First group than for the Filler-First group?): we regressed length-corrected RTs during the disambiguating region onto group (RC-First vs. Filler-First), ambiguity (ambiguous vs. unambiguous), and the interaction between these two variables. Again, there was a main effect of ambiguity RCs (β=19, p<.05). There was also a main effect of group: subjects in the RC-First group had overall faster reading times (β=-7, p<.05). Crucially, the two-way interaction between ambiguity and group was marginally significant (β=-5, p=.08): the ambiguity effect was smaller in the RC-First group than in the Filler-First group. That is, reading a block of filler sentences does not reduce the processing cost of RCs to the same extent that reading a block of RCs does. This result is shown by the pairs of bars corresponding to block 2 for both groups in Figure 2.

Prediction 3 (is the ambiguity effect for MVs in block 3 greater for subjects who have seen more RCs, i.e. for the RC-First group?): We regressed length-corrected RTs during the disambiguating region of sentences read during block 3 onto ambiguity (ambiguous MV vs. unambiguous MV), group (RC-First vs. Filler-First), and the interaction between these variables. There was a main effect of ambiguity, such that ambiguous MVs were read more

slowly than unambiguous MVs (β=8, p<.05). The main effect of group did not reach significance (β=4, p=.3). Crucially, the two-way interaction between ambiguity and group was significant (β=5, p<.05): the ambiguity effect for MVs during block 3 was greater for the RC-First group than for the Filler-First group. In other words, subjects who read more RCs subsequently experienced both (1) a reduction in the ambiguity effect for RCs and (2) an increase in the ambiguity effect for MVs. This pattern is visualized in Figure 2 in the right-most pair of bars for each group.

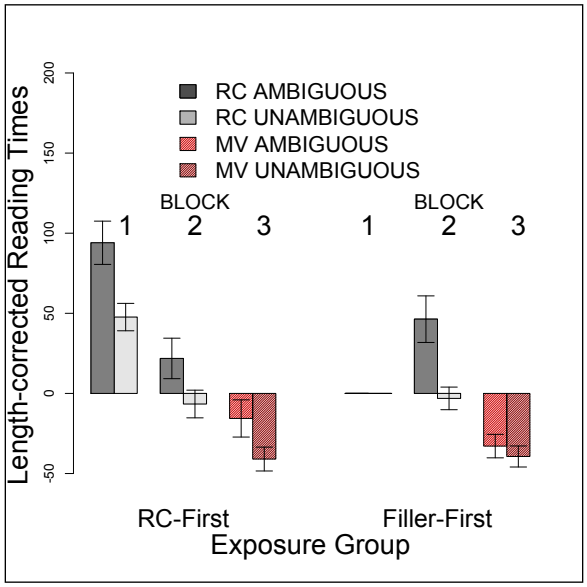

Figure 2: Mean length-corrected RTs during the disambiguating region for ambiguous and unambiguous conditions across all three blocks of Experiment 2. Error bars give 95% confidence intervals on the mean.

Discussion

Experiment 2 was designed to further address the hypothesis that comprehenders adjust their syntactic expectations to converge towards the statistics of the input. Specifically, we predicted that, since RCs and MVs compete with each other for probability mass, when subjects come to assign a higher probability to one structure, they should come to assign a lower probability to the other. In Experiment 2, this led to the concrete prediction that a diminished ambiguity effect for RCs should lead to a larger ambiguity effect for MVs, and that this should be greater for the RC-first relative to the Filler-first group. This is what we observed (cf. Figure 2).

General Discussion

We tested the hypothesis that language comprehenders are able to adapt their syntactic expectations to novel linguistic environments according to the statistics of those environments. In two reading experiments, we provided subjects with experience with distributions of syntactic structures that diverged sharply from their previous experience with English. We predicted that subjects would adapt their expectations (as reflected in changes in RTs) according to their cumulative recent experience. As predicted, in Experiment 1 subjects came to process a priori infrequent structures that had initially produced longer RTs more quickly when those structures were frequent in the experiment. Experiment 2 replicated this and went a step further: there, subjects not only came to process an a priori infrequent structure more quickly, but also came to process an a priori frequent structure *more slowly* when it was infrequent in the experiment. Our experiments suggest that readers are capable of adapting to the *relative* frequencies (/probabilities) of syntactic structures in the current linguistic environment. The results of our experiments have implications for questions concerning the mechanisms underlying language comprehension and for debates about the mechanism underlying syntactic priming. We discuss these in turn.

Previous work on syntactic adaptation has demonstrated that exposure to syntactic structures can have immediate (Traxler, 2008) and cumulative (Kaschak & Glenberg, 2004) effects on language comprehension, that these effects can be indexed to individual talkers (Kamide, 2012), and that the effects may endure for several days (Wells et al., 2009). Moreover, work on statistical learning has demonstrated a remarkable capacity in children and adults to rapidly extract statistical regularities in novel artificial languages (cf. Gómez & Gerken, 2000), and has suggested that statistical learning may correlate with language processing in general (Misyak & Christiansen, 2012). As mentioned in the introduction, however, previous work on experience-based processing, syntactic priming, and statistical learning has all proceeded largely in parallel, and has left open the question of how the immediate effect of experience on language comprehension accumulates over time to give rise to cumulative priming, experience-based processing effects, and environment-specific adaptation. We have attempted to build on all of this work by demonstrating that syntactic adaptation can be profitably construed as the rapid, incremental, and cumulative convergence towards the statistics of a novel linguistic environment. Syntactic adaptation of the kind observed here may therefore offer a route by which the immediate effects of experience ("priming") accumulate to give rise to long-term experience-based processing.

Our results also speak to ongoing debates surrounding the type of mechanism that underlies syntactic priming. Two main views have emerged from previous work. Transient activation accounts hold that priming results from a short-lived boost in the activation of a syntactic representation (Pickering & Garrod, 2004). By contrast, implicit learning accounts hold that priming is a consequence of an implicit learning mechanism (Chang, Dell, & Bock, 2006). We believe that implicit learning accounts cover the current results most naturally for at least two reasons. First, subjects in both experiments were sensitive to the cumulative statistics of the environment: the degree to which subjects' expectations for a structure had changed at a given point in the experiment depends on how many times

subjects saw (a) that structure and (b) other structures competing with it for probability mass. To the extent that transient activation accounts do not predict cumulative priming and insofar as learning accounts do (cf. Kaschak, Loney, & Borreggine, 2006), our results appear to support an implicit learning account. Second, our results provide indirect evidence for error-sensitivity: we observed changes in RTs over the course of both experiments for both RCs and MVs, but changes of a greater magnitude for RCs relative to MVs (see Figure 2): observing a low-probability linguistic event (and therefore one with a relatively large error signal) leads to greater changes in RTs. Error-sensitivity has been argued to be a hallmark of implicit learning (Chang et al., 2006; Fine & Jaeger, 2013; Jaeger & Snider, 2013).

Taken together with recent work on adaptation in phonetics and pragmatics (Kurumada, Brown, & Tanenhaus, 2012; Norris, McQueen, & Cutler, 2003), our results suggest that adaptation is likely to be a general property of language processing, and a manifestation of a general ability to cope with a dynamic environment.

Finally, our findings demonstrate the fundamental role that experience plays in language processing. Our work suggests that not only is language processing influenced by aggregated prior experience (e.g., MacDonald et al., 1994), but that experience incrementally and rapidly shapes our expectations about the language we speak, thereby allowing us to comprehend language more efficiently.

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