Syntactic satiation is driven by speaker-specific adaptation

Jiayi Lu, Daniel Lassiter, Judith Degen
{jiayi.lu, danlassiter, jdegen}@stanford.edu
Department of Linguistics, Stanford University
Stanford, CA 94305, USA

Abstract

Listeners adapt to variability in language use by updating their expectations over variants, often in speaker-specific ways. We propose that adaptation of this sort contributes to *satiation*, the phenomenon whereby the acceptability of unacceptable sentences increases after repeated exposure. We provide support for an adaptation account of satiation by showing that the satiation of purportedly unacceptable island-violating constructions demonstrates speaker-specificity, a key property of adaptation.

Keywords: psycholinguistics; experimental syntax; adaptation; satiation; acceptability judgments

Introduction

In experimental syntax, sentence grammaticality is often probed using acceptability judgments (Schütze, 1996). One commonly held assumption is that the contrasts in sentence acceptability approximate the contrasts in grammaticality. Recent studies show acceptability judgments of sentences often increase throughout experiments (Brown, Fanselow, Hall, & Kliegl, 2021; Chaves & Dery, 2019; Francom, 2009; Goodall, 2011; Hiramatsu, 2001; Snyder, 2000), a phenomenon called *satiation*. Assuming grammars are stable over the course of an experiment, satiation challenges the link from grammaticality to acceptability (Schütze, 1996).

To better understand the factors besides grammaticality that affect acceptability, we investigate the mechanism underlying satiation. Specifically, we test whether satiation is driven by updates in participants' beliefs about the conditional probability of a syntactic construction, an effect also known as *syntactic adaptation* (Fine, Jaeger, Farmer, & Qian, 2013; Kamide, 2012). We build on the linking hypothesis that constructions' greater expectedness leads to higher acceptability ratings (Lau, Clark, & Lappin, 2017) and test whether satiation of initially unacceptable island-violating sentences demonstrates a key property of adaptation: speaker-specificity.

Syntactic satiation

In an early experimental study on satiation, Snyder (2000) used a 2AFC task ("acceptable"/"unacceptable") to test participants' responses to seven island-violating constructions (i.e. sentences with illicit wh-movements from within particular constituents that block movement). Participants gave significantly more "acceptable" ratings towards the end of the experiment compared to the beginning, for three constructions: *whether*-islands (e.g., *Who does John wonder whether Mary likes?*), subject islands (e.g., *What does John know that a bottle of fell on the floor?*), and complex-NP islands (e.g., *Who does Mary believe the claim that John likes?*).

Proposals for the mechanism underlying the observed satiation effect include a task-specific equalization strategy (Sprouse, 2009), a bottleneck in memory (Francom, 2009; Hofmeister & Sag, 2010), and priming (Do & Kaiser, 2017; Francom, 2009). We briefly review these proposals to set the stage for our novel proposal: that satiation is underlyingly speaker-specific adaptation.

Sprouse (2009) claims that the satiation effect observed by Snyder (2000) is the result of an "equalization strategy" whereby participants aim to balance the positive and negative judgments they provide over the course of the experiment. When there are more unacceptable sentences in the stimulus set, participants give increasingly higher ratings throughout the experiment to balance the overall responses. If true, researchers would be mistaken in concluding that test items indeed become more acceptable with repeated exposure.

Francom (2009) proposes the memory bottleneck account of satiation: satiation is the result of facilitation in the processing of memory-demanding structures with repeated exposure. This account considers the allocation of memory to sentence processing to be flexible. Assuming that the low acceptability of island-violating constructions partially results from memory-related processing difficulties (Hofmeister & Sag, 2010), increased acceptability after repeated exposure may reflect facilitation in the processing of island-violating constructions via memory resource re-allocation.

In addition to the memory bottleneck account, Francom (2009) speculates that syntactic priming (i.e., facilitation in the processing and production of structures via exposure) could be another source of satiation. This is supported by the reduction in reading time for satiated constructions, a hallmark of syntactic priming

(Kaschak & Glenberg, 2004; Tooley, Traxler, & Swaab, 2009). Do and Kaiser (2017) also proposed that priming could drive satiation. However, the nature of priming itself is under debate. Some view priming as an increase in transient activation of lexical and structural representations (Pickering & Branigan, 1998). Others claim that priming is driven by implicit learning of structures' frequency distributions (Bock & Griffin, 2000; Chang, Dell, & Bock, 2006; Kaschak, Kutta, & Jones, 2011). Thus, priming accounts of satiation can be interpreted differently based on the priming mechanism assumed.

In sum, the mechanism underlying satiation is still far from clear. We build on the priming-based account of satiation that assumes an implicit learning mechanism for priming, and propose that satiation is the result of syntactic adaptation. Particularly, we propose that participants update their beliefs about a structure's production probability through repeated exposure, which is reflected in a structure's acceptability. Moreover, such belief updating should exhibit a hallmark of adaptation, *speaker-specificity*, which is not predicted by either the equalization strategy or the memory bottleneck account. We elaborate on the adaptation account of satiation next.

An adaptation account of satiation

Previous studies have revealed a remarkable degree of linguistic intra- and inter-speaker variability (Adger & Smith, 2005; Allen, Miller, & DeSteno, 2003; Biber, 1995; Labov, 1972). To recover a speaker's intended meaning and predict the upcoming linguistic signal, listeners need to model the sources of variability in language use. Studies show that listeners achieve this through *adaptation*: they track both speaker identity and contextual information that conditions the observed variability, and update their expectations over variants accordingly (Bradlow & Bent, 2008; Brennan & Clark, 1996; Kleinschmidt & Jaeger, 2015; Schuster & Degen, 2020; Yildirim, Degen, Tanenhaus, & Jaeger, 2016). One domain in which listeners exhibit adaptation is syntax: listeners track speaker-specific preferences for different PP-attachment sites (Kamide, 2012) and display decreased processing difficulty for garden-path sentences after repeated exposure (Fine et al., 2013; Fine & Jaeger, 2016). This suggests that listeners can rapidly update their expectations for syntactic structures.

Recent work proposes that syntactic adaptation can be formalized as Bayesian belief-updating (Fine, Qian, Jaeger, & Jacobs, 2010): listeners manage the variability in the input by maintaining a probability distribution over speaker-specific generative language models (ϑ). A generative language model decides the probability distribution of linguistic representations (LR; e.g. syntactic structures, lexical items, prosodic structures, etc.) in a context, which further decides the probability distribution of the output utterance (u). This process is shown in the causal model in Fig. 1.

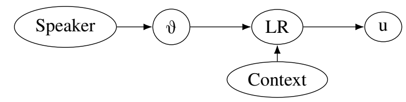

Figure 1: Causal model of utterance production.

We remain agnostic about ϑ's internal structure, and simply assume that it can assign production probabilities to syntactic structures. We further assume that listeners come into an utterance context evaluating the probability distribution over a hypothesis space Θ of possible generative language models. The probability of each generative language model $\vartheta \in \Theta$ given a speaker s is updated via Bayesian belief updating based on an observed utterance u in a context c:

$$p(\vartheta \mid u, s, c) \propto p(u \mid \vartheta, s, c)\ p(\vartheta \mid s, c) \qquad (1)$$

As shown in Fig. 1, speaker and utterance are conditionally independent given ϑ. Furthermore, we make the following assumption: we assume a simplistic experimental environment where the context is fixed and given, and the production probability of utterances is only modulated by the syntactic structure among all linguistic representations (LR). We assume participants can recover a single syntactic structural from each utterance (i.e. there is no syntactic ambiguity). Equation (1) thus simplifies to (2), where x is the syntactic structure of u.

$$p(\vartheta \mid x, s) \propto p(x \mid \vartheta)\ p(\vartheta \mid s) \qquad (2)$$

For any two generative models ϑ_i and ϑ_j where $p(x \mid \vartheta_i) > p(x \mid \vartheta_j)$, it follows from (2) that the probability of ϑ_i increases compared to ϑ_j as a result of adaptation:

$$\frac{p(\vartheta_i \mid x, s)}{p(\vartheta_j \mid x, s)} > \frac{p(\vartheta_i \mid s)}{p(\vartheta_j \mid s)} \qquad (3)$$

This belief updating process, though not directly observable, can lead to changes in a listener's structural expectations, which can further be observed as changes in sentence acceptability ratings. The listener's expectation for a structure x can be expressed as a marginal probability over generative models:

$$p(x \mid s) = \sum_{\vartheta \in \Theta} p(x \mid \vartheta) p(\vartheta \mid s) \qquad (4)$$

It follows from (2) and (3) that $p(x \mid s)$, the listener's belief about the production probability of structure x, increases with exposure to x as a result of the belief updating process (except for the boundary case where all $\vartheta \in \Theta$ assign the same $p(x \mid \vartheta)$ to x, in which case $p(x \mid s)$ remains constant).

Sentence acceptability can be predicted by the sentence's overall expectedness (Lau et al., 2017). We thus assume the following linking hypothesis: all else equal, the acceptability of a structure x produced by speaker s, $A(x \mid s)$, increases monotonically with $p(x \mid s)$. With this linking hypothesis we can explain the satiation effect: repeated exposure leads to an increase in $p(x \mid s)$, which consequently leads to an increase in $A(x \mid s)$.

This account makes the crucial prediction that satiation should be speaker-specific: listener exposure to only speaker s producing x should lead to a greater increase in $A(x \mid s)$ than in $A(x \mid s')$ for a different speaker s'.[1]

We conducted two experiments to test the satiation-as-adaptation account. Exp. 1 establishes the satiation of island-violating constructions beyond the effects of equalization strategies. Exp. 2 tests whether satiation demonstrates the predicted speaker-specificity.

Exp. 1: Satiation beyond equalization

In an acceptability rating task, we tested whether island-violating constructions demonstrate satiation at all. To control for the equalization strategy, we included an equal number of ungrammatical and grammatical fillers.[2] If island-violating constructions satiate independently of the equalization strategy, acceptability ratings should increase throughout the experiment.

Methods

Participants were 120 participants on Mechanical Turk, with 14 excluded because their primary language was not English, or the 95% confidence intervals of responses to grammatical and ungrammatical fillers overlapped, or they answered any of the practice trials incorrectly more than once[3].

Materials and procedure. We tested the three island-violating constructions shown to satiate in Snyder (2000): complex-NP islands, subject islands, and *whether*-islands. Each target sentence was presented with a context sentence. Also included in the stimuli were grammatical fillers and ungrammatical word-salad fillers. Grammatical filler items were regular wh-questions. Ungrammatical fillers were wh-questions with permuted word-order starting at the second word. Example items of all conditions are shown in Table 1.

The experiment contained 15 blocks, with each block containing three island items (one in each condition), one grammatical and one ungrammatical filler. The order of items and blocks was randomized. Three lists were created in a Latin Square fashion. On each trial, participants rated the acceptability of the target sentence using a slider bar with endpoints labeled "completely unacceptable" and "completely acceptable". Responses were recorded as numeric values between 0 (completely unacceptable) and 1 (completely acceptable).

Results and discussion

Mean acceptability ratings as a function of trial number are shown in Fig. 2. We used a linear mixed-effects model predicting acceptability rating from dummy-coded fixed effects of trial number, condition (reference level: "grammatical filler"), and their interactions to assess whether satiation occurred in the experiment. If grammatical fillers do not satiate, island-violating sentence satiation should be evidenced in significantly positive coefficients for the interaction between trial number and the island condition contrasts. Random by-participant and by-item intercepts were included, as well as by-participant and by-item slopes for the fixed effects.

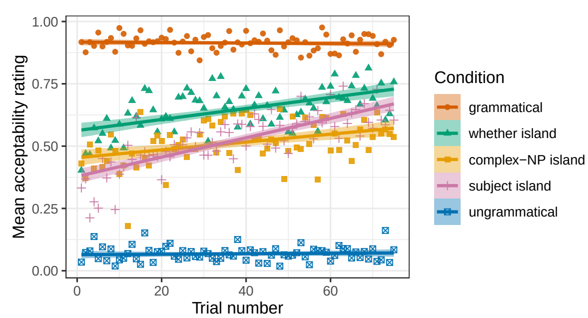

Figure 2: Mean by-condition and by-trial acceptability ratings (Exp. 1).

[1] $A(x \mid s')$ could still increase due to generalization across speakers, an effect widely attested in the adaptation literature (Bradlow & Bent, 2008; Kleinschmidt, 2019; Schuster & Degen, 2019; Xie et al., 2018).

[2] The grammaticality of island-violating sentences is controversial (Hofmeister, Casasanto, & Sag, 2013; Kluender & Kutas, 1993), so we categorized them as neither grammatical nor ungrammatical when balancing the stimuli in Exp. 1. In a separate experiment (n=200, 54 excluded by the same exclusion criteria as in Exp.1), we instead adopted the assumption that island-violating sentences are ungrammatical (Chomsky, 1986; Ross, 1967). We thus balanced island-violating sentences and ungrammatical fillers jointly against grammatical fillers. The experimental paradigm and the test conditions were identical to Exp.1, but we included 45 island-violating items (15 of each island-violating construction), 4 word-salad fillers, and 49 grammatical fillers. Results were qualitatively identical to Exp. 1: using the same statistical model, there were significant interactions of *trial number* with *condition* for all three island-violating constructions (*whether*-island: β=0.0008, SE=0.0003, t=3.13, $p<0.01$; complex-NP: β=0.0009, SE=0.0003, t=3.48, $p<0.01$; subject island: β=0.001, SE=0.0003, t=3.61, $p<0.01$). This suggests that the satiation observed in the current experiment generalizes across qualitatively different ways of balancing grammatical and ungrammatical stimuli, and is not an artifact of treating island-violating sentences as neither grammatical nor ungrammatical.

[3] The three exclusion criteria excluded 0, 14, and 2 participants respectively. Some participants failed more than one exclusion criteria.

Table 1: Example stimuli.

Condition	Context	Target
Complex-NP island	The teacher believes the claim that the girl lost her wallet.	What does the teacher believe the claim that the girl lost?
Subject island	The detective thinks that a bottle of poison killed the man.	What does the detective think that a bottle of killed the man?
Whether-island	The teacher wonders whether the student spilled a cup of coffee.	What does the teacher wonder whether the student spilled?
Grammatical filler	The journalist thought that the politician wrote a book.	What did the journalist think that the politician wrote?
Ungrammatical filler	The priest of the local church saw a man sleeping under the bridge.	What bridge the under saw church local the of did priest the?

Sentences in the island conditions were rated less acceptable than the grammatical fillers (*whether*-island: β=-0.36, SE=0.040, t=-8.91, p<0.001; complex-NP island: β=-0.47, SE=0.043, t=-11.0, p<0.001; subject island: β=-0.54, SE=0.038, t=-14.0, p<0.001). There was no significant main effect of *trial number* (β=0.0001, SE=0.0002, t=0.44, p=0.66). There were significant interactions of *trial number* with *condition* for the *whether*-island contrast (β=0.0024, SE=0.0004, t=5.77, p<0.001), the complex-NP island contrast (β=0.0018, SE=0.0005, t=3.42, p<0.01), and the subject island contrast (β=0.0039, SE=0.0005, t=7.27, p<0.001), suggesting that all three island conditions satiated. Ungrammatical fillers did not satiate (interaction with trial number: β=0.0002, SE=0.0003, t=0.58, p=0.56).

These data challenge the equalization strategy account (Sprouse, 2009): if an equalization response strategy alone was the driving force behind the increase in acceptability ratings, the cumulative response mean across all conditions should drift towards the midpoint of the scale. However, the cumulative mean crossed the midpoint (0.5) and continued to increase throughout the experiment (see Fig. 3). This suggests that an equalization strategy is not the sole reason for satiation.

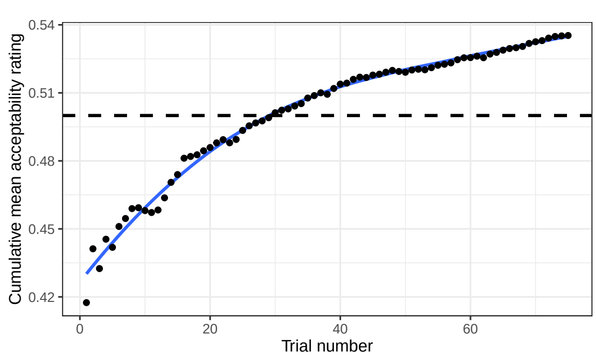

Figure 3: Cumulative response mean across all conditions in Exp. 1. Dashed line indicates scale midpoint.

Exp. 2: Speaker-specific satiation

Thus far, we have shown that all three island-violating sentence types satiate, and that satiation cannot be explained by an equalization response strategy alone. In Exp. 2, we test in an exposure-and-test paradigm whether satiation is driven by speaker-specific adaptation, by overtly matching each construction consistently with one speaker during exposure. If satiation is the result of speaker-specific adaptation, it should show speaker-specificity: acceptability should increase during exposure, but should decrease on test if the construction is produced by a novel speaker.

Methods

Participants were 360 Mechanical Turk participants with the same three exclusion criteria as Exp. 1 (89 excluded)[4].

Materials and procedure. Exp. 2 tested the same sentences as Exp. 1, but each participant only saw one of the three island conditions (random between-participant assignment). The experiment consisted of 15 exposure and 6 test blocks. Each block contained one island item, one grammatical, and one ungrammatical filler (same fillers as in Exp. 1). Each item was presented as having been produced by an accompanying cartoon avatar.

Three avatar-represented speakers were matched with each sentence during exposure. On test, island and grammatical filler speaker assignment was either maintained (*speaker match*) or reversed (*speaker mismatch*) via random between-participant assignment). To control for any stereotypical perception of the avatars, the speakers for island and grammatical filler items were randomly drawn from a pool of four and assigned to sentence types. An exception is the ungrammatical fillers, which were always produced by a robot named "Iron-Head". The pool of human speakers and "Iron-Head" is shown in Fig. 4.

[4]The three exclusion criteria excluded 3, 64, and 55 participants respectively. Some participants failed more than one criteria.

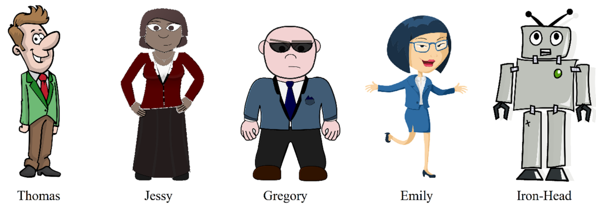

Figure 4: Speaker names and avatars.

Results and discussion

Mean acceptability ratings during exposure are shown in Fig. 5. We applied the same mixed-effects analysis as in Exp. 1 to assess satiation.

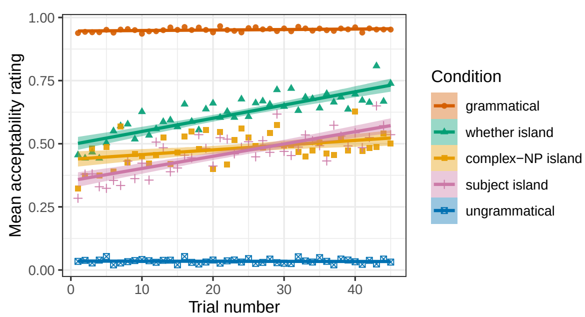

Figure 5: Mean by-condition and by-trial acceptability ratings in Exp. 2.

Each island-violating sentence type was less acceptable than the grammatical fillers (*Whether*-island: β=-0.45, SE=0.016, t=-27.7, $p<0.001$; complex-NP island: β=-0.51, SE=0.018, t=-28.8, $p<0.001$; subject island: β=-0.60, SE=0.016, t=-36.2, $p<0.001$). There was no significant main effect of *trial number* (β=0.0002, SE=0.0002, t=1.05, p=0.29), but there were significant interactions of *trial number* and *condition* for *whether*-islands (β=0.0051, SE=0.0005, t=9.31, $p<0.001$), complex-NP islands (β=0.0016, SE=0.0006, t=2.43, $p<0.05$), and subject islands (β=0.0046, SE=0.0005, t=10.21, $p<0.001$), suggesting that all three island conditions satiated, replicating Exp. 1.

Mean acceptability ratings for each test condition are shown in Fig. 6. To assess whether satiation exhibits speaker-specificity, test phase ratings were analyzed using linear mixed-effects regression with fixed effects of test condition (speaker match vs. speaker mismatch, reference level: "speaker match"), dummy-coded sentence condition (reference level: "grammatical filler"), and their interaction. If satiation is driven by speaker-specific adaptation, test phase acceptability should be lower in the speaker mismatch than speaker match condition. Speaker-specificity should emerge as a significant interaction of *sentence condition* and *test condition*. Random by-participant and by-item intercepts, and by-item slopes for the fixed effects were included. There were

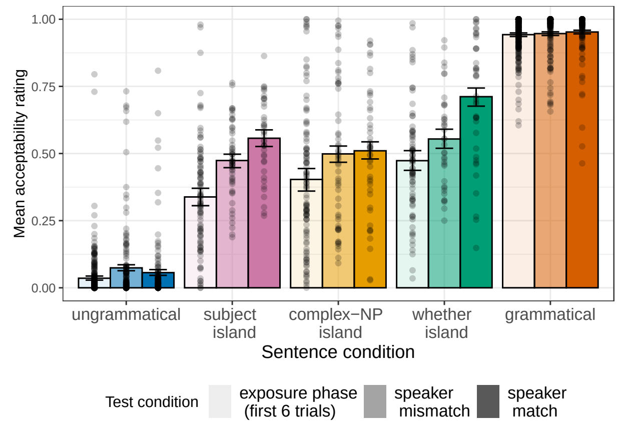

Figure 6: Mean acceptability ratings in test phase of Exp. 2. Colors indicate same conditions as in Fig. 5. Dots indicate by-participant means.

significant interactions of sentence condition and test condition for *whether*-islands (β=0.15, SE=0.031 t=4.86, $p<0.01$) and subject islands (β=0.073, SE=0.020 t=3.59, $p<0.01$), but not for complex-NP islands (β=0.0090, SE=0.018 t=0.50, p=0.62). This suggests that satiation of subject- and *whether*-island violating sentences is speaker-specific. The lack of conclusive evidence for the speaker-specific adaptation in complex-NP islands may be due to the already smaller satiation effect size for this sentence type.

If speaker-specific adaptation is the sole contributor to satiation, acceptability prior to satiation should not differ from the speaker mismatch test condition. Fig. 6 shows mean acceptability ratings on the first 6 trials in the exposure phase, which we treat as pre-satiation ratings. To test for a difference, we ran a linear mixed-effects model with fixed effects of *sentence condition* (reference level: 'grammatical fillers') and *phase* (pre-satiation vs. speaker mismatch, reference level: 'pre-satiation') with random by-participant and by-item intercepts and by-item slopes for the fixed effects.

There were significant interactions of sentence condition and phase for *whether*-islands (β=0.080, SE=0.036 t=2.21, $p<0.05$), subject islands (β=0.13, SE=0.025 t=5.04, $p<0.001$), and complex-NP islands (β=0.0080, SE=0.029, t=2.71, $p<0.05$). This means that the acceptability increase gained through satiation was not entirely eradicated by switching speakers, suggesting that satiation is partly speaker-general.

General Discussion

Two experiments established (a) that satiation of island-violating constructions is not just attributable to an equalization strategy, and (b) that satiation exhibits speaker-specificity. These results are predicted by the adaptation account we put forth: if driven by speaker-specific adaptation, satiation should be specific to the speakers that produce the observed constructions, which is exactly what we observed in Exp. 2. We take this as further evidence that rapid on-line adaptation extends to anomalous syntactic constructions (Kaschak & Glenberg, 2004).

The results challenge both memory re-allocation and an equalization strategy as the only sources of satiation (Sprouse, 2009; Francom, 2009), though they may be contributing factors. The memory bottleneck account could be modified such that listeners' memory re-allocation is speaker-specific. Like the adaptation account, this modified version of the memory bottleneck account would assume that listeners keep track of the distribution of structures by speaker.

Some questions remain. First, satiation does not equally affect all sentences with degraded acceptability. We observed that the ungrammatical word-salad fillers do not satiate. Furthermore, the complex-NP island sentences satiate to a lesser degree compared to the other two island-violating constructions. Note that we also observed in Exp. 2 that the satiation of the complex-NP island sentences does not demonstrate speaker-specificity, while the satiation of *whether*-island sentences and subject island sentences does. Below we discuss possible explanations for these differences between sentence types.

One possible explanation comes from Brown et al. (2021), who found that satiation only affects sentences that are grammatical and have a middle-of-the-scale acceptability rating. The ungrammatical fillers do not satisfy either criterion. The lower rate of satiation in complex-NP island sentences could be explained if they are ungrammatical while *whether*-island and subject island sentences are grammatical. However, it is unclear why the three island-violation types should have different grammaticality status despite having comparable levels of acceptability.

Another explanation is suggested by the previous literature on priming, which shows that structures with lower prior probability have greater priming effects than more likely structures (Ferreira, 2003; Fine et al., 2013; Fraundorf & Jaeger, 2016; Kaschak et al., 2011). If the complex-NP island sentences have a higher prior probability of occurrence compared to the other sentence types, their lower rate of satiation could be explained. However, the ungrammatical fillers should have the lowest prior probability among all sentence types, yet they show no satiation, contrary to the simplest prediction of this account. This raises the question of where the limits of error-driven learning lie.

A third explanation, which may also provide a partial answer to the question of limits on error-driven learning, is that the tested sentences may be variably comprehensible. It is possible that, for syntactic adaptation to occur, listeners must recover an interpretation for the observed string, in order for there to be a representation that beliefs can be updated about in the first place. If the complex-NP island sentences and the ungrammatical fillers are on average more difficult or impossible to retrieve an interpretation for, there simply may not be any systematicity in representation for participants to adapt to, resulting in the lower observed rates of adaptation compared to the more comprehensible sentence types.

A second open question concerns sources of satiation other than speaker-specific adaptation. Results from Exp. 2 suggest that speaker-specific adaptation can only account for part of the acceptability increase. One possibility is that participants also underwent speaker-general adaptation. Through repeated exposure to utterances of the same structure, the listener's expectation for that structure to occur regardless of the speaker may also increase, leading to speaker-general satiation (Bradlow & Bent, 2008; Kleinschmidt, 2019; Schuster & Degen, 2020; Xie et al., 2018). Another possibility is that non-adaptation factors, e.g. an equalization strategy or memory re-allocation, may also contribute to satiation.

In conclusion, we showed that island-violating constructions demonstrate satiation which can be partially explained as the result of speaker-specific adaptation.

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