Complexity Bias and Substantive Bias in Phonotactic Learning
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1. Background: Synchronic Learning Biases in Phonological Learning

- To what extent is the phonological typology shaped by synchronic learning biases?
- Synchronic (analytic) bias: Learners biased toward acquiring certain phonological systems over others
  - Complexity bias: bias against formally complex patterns
  - Substantive/naturalness bias: bias against phonetically unnatural patterns
- Research question: Does phonetic naturalness bias phonotactic learning?
- Approach: Test whether learners reproduce attested and phonetically-motivated phonotactic implicationals in artificial grammar learning (AGL) experiments

1.1 Past Research on Synchronic Biases

- A number of studies have uncovered evidence for complexity bias: learners acquire featurally simpler phonological patterns better (e.g. Moreton 2008; Hayes et al. 2009; Skoruppa & Peperkamp 2011; Moreton 2012)
- Other studies have found evidence for substantive bias: learners prefer to acquire phonetically natural patterns and underlearn phonetically unnatural patterns (e.g. Wilson 2006; Becker, Kretz & Nevins 2011; Becker, Nevins & Levine 2012; Finley 2012; Hayes & White 2013; White 2013)
  - However, some studies that purport to find a naturalness bias could be reinterpreted as having found a complexity bias instead (Becker, Kretz & Nevins 2011; Hayes & White 2013)
  - Others have a pattern of results that is not fully consistent with a naturalness bias account (Wilson 2006)
- Most of these studies have used an AGL paradigm
- Moreton & Pater’s (2012a,b) review of work in this area concluded that there is fairly robust evidence for complexity bias but scant evidence for substantive bias

1.2 Synchronic Biases in Phonotactic Learning

- Investigations of substantive bias have focused mostly on alternations
- A few studies have tested naturalness bias in phonotactic learning:
  - Support for substantive bias:
    - Underlearning of unnatural phonotactic generalizations supported by the English lexicon (Hayes & White 2013)—however, unnatural generalizations were also more complex
  - Lack of support for substantive bias:
    - Equal learning of natural and unnatural phonotactics (Skoruppa & Peperkamp 2011; Myers & Padgett 2014; Greenwood 2016—casual speech condition)
    - Unnatural phonotactic generalization learned better than a natural phonotactic generalization (Greenwood 2016—careful speech condition)
- My approach investigates not just phonotactic restrictions but phonotactic implicationals about the existence of contrasts in different positions
  - Implicitly asking learners to compare existence of contrasts across positions may cause a bias to emerge when simply testing learnability of a specific phonotactic constraint doesn’t
2. Experiment 1: Positional Extension of an Obstruent Voicing Contrast

2.1 The Phonotactic Implicational

- If a language contrasts voicing in obstruents word-finally (e.g. /ap/ vs. /ab/), it will contrast voicing in obstruents word-initially (e.g. /pa/ vs. /ba/), but not necessarily vice versa
- Phonetic motivation: cues to obstruent voicing more abundant word-initially than word-finally; in particular, VOT available word-initially but not word-finally (Steriade 1997)
  - Voiced and voiceless obstruents should be more perceptually similar (i.e. harder to distinguish) at the end of a word than at the beginning of a word
  - If voicing contrast exists word-finally, where it is harder to perceive, it should exist word-initially, where it is easier to perceive (T/D# → #T/D)
- Implicational supported by the typology (Steriade 1997, Lombardi 1999)

2.2 Method

- Expose subjects to an obstruent voicing contrast in word-initial or word-final position and test whether they extend the contrast to the other position
- In addition to manipulating position of contrast, manipulated what value voicing “neutralizes” to
- Four training conditions defined on two dimensions: Trained Contrast Position and Trained Neutralization Value

Table 1: Training Conditions

<table>
<thead>
<tr>
<th></th>
<th>#T</th>
<th>#D</th>
<th>T#</th>
<th>D#</th>
</tr>
</thead>
<tbody>
<tr>
<td>#D…{T, D}# (*#T)</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>#T…{T, D}# (*#D)</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>{T, D}…D# (*T#)</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>{T, D}…T# (*D#)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>

**Bold** = Word-final contrast  
**Italics** = Neutralizing-to-T

Table 2: Sample Training Items in the #{T, D}…T# (*D#) Condition

<table>
<thead>
<tr>
<th>#T</th>
<th>#D</th>
<th>T#</th>
<th>D#</th>
</tr>
</thead>
<tbody>
<tr>
<td>pímir</td>
<td>bímir</td>
<td>míwip</td>
<td>lanít</td>
</tr>
<tr>
<td>tilár</td>
<td>dirín</td>
<td></td>
<td>nuwák</td>
</tr>
<tr>
<td>kawám</td>
<td>gawám</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| ... | ... | ... | ...

- Properties of items (training and test)
  - CVCVC3 shape
  - C1 or C3 a stop drawn from [p t k b d g]
  - Other two Cs sonorants drawn from [m n l j w] (no final [j]s or [w]s, no [ji]s or [wu]s)
  - Vs drawn from [i a u]
  - Bilabial, alveolar, and velar stops equally represented
  - Half of items belong to minimal pairs
  - Half iambs, half trochees (stress not correlated with position featuring the voicing contrast or position containing a stop)
• Experiment conducted online using Experigen (Becker & Levine 2013)

• Training Phase
  ➢ Subjects told they would be listening to some words of a new language
  ➢ 2 blocks of the same 36 training items
  ➢ Each training item paired with an image

• Test Phase
  ➢ Subjects heard additional words and had to say whether the word could be a word of the language they had been listening to or not (Yes/No)
  ➢ 1 block of 48 test items: #T, #D, T#, and D# items (same for all conditions)
  ➢ No images

• Three types of test items:
  ➢ *Familiar Conforming*: voicing and position conform to trained pattern, and item heard in training
  ➢ *Novel Conforming*: voicing and position conform to trained pattern, but item not heard in training
  ➢ *Novel Nonconforming*: voicing and position combination not heard in training

<table>
<thead>
<tr>
<th>Table 3: Sample Test Items for Each Training Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>#D…{T, D}# (*#T)</td>
</tr>
<tr>
<td>nimáp</td>
</tr>
<tr>
<td>#T…{T, D}# (*#D)</td>
</tr>
<tr>
<td># {T, D} ... D# (*T#)</td>
</tr>
<tr>
<td># {T, D} ... T# (*D#)</td>
</tr>
</tbody>
</table>

2.3 Participants

• Native English speakers recruited through UCLA Psychology Subject Pool
• 149 subjects, divided among 4 conditions (subjects per condition ranged from 33 to 41)

2.4 Predictions

• Subjects’ acceptance rates of Novel Nonconforming items (relative to Novel Conforming items) indicate whether they have extended the obstruent voicing contrast to a new position in a given condition

**Hypothesis**

1. **Substantive bias hypothesis** (position—Trained Contrast Position):
   • Recall the phonotactic implicational: T/D# → #T/D, but not vice versa
   • Behavior consistent with implicational would be asymmetric extension: subjects exposed to contrast word-finally should extend it to word-initial position **more** than subjects exposed to contrast word-initially extend it to word-final position

**Predicted Relative Acceptance Rates of Novel Nonconforming Items by Condition**

- Erroneously accepting
  - #T #D #T #D
  - Correctly rejecting
#2 Substantive bias hypothesis (voicing—Trained Neutralization Value):
- Voiced obstruents more marked than voiceless obstruents → more extension from voiced to voiceless obstruents than from voiceless to voiced obstruents

#3 Substantive bias hypothesis (position and voicing):
- More extension from word-final to word-initial position AND more extension from voiced to voiceless obstruents

#4 Complexity bias hypothesis:
- Post-hoc, but turned out to provide best account, so presented here for clarity
- Due to presence of sonorant Cs in training items, constraint needed to exclude Novel Nonconforming items in neutralizing-to-T conditions could be more complex than constraint needed in neutralizing-to-D conditions

- Predicts more “extension” from voiceless to voiced obstruents than from voiced to voiceless obstruents (opposite of voicing-related Hypothesis #2 above)

2.5 Results
- Figure 1 shows the acceptance rates of the three types of test items across conditions:
• Acceptance rates of Novel Conforming items:
  ➢ Above chance in all conditions (generalization → learning of trained pattern)
  ➢ Not significantly different across conditions
• Mixed-effects logistic regression fit to Novel Nonconforming items:
  ➢ Dependent variable: response (accept or reject)
  ➢ Fixed effects: Trained Contrast Position and Trained Neutralization Value
  ➢ Random intercepts for subject and item
• Predictions:
  ➢ Position-based substantive bias: Main effect of Trained Contrast Position such that Novel Nonconforming acceptance rates higher in word-final contrast conditions than in word-initial contrast conditions
  ➢ Complexity bias: Main effect of Trained Neutralization Value such that Novel Nonconforming acceptance rates higher in neutralizing-to-T conditions than in neutralizing-to-D conditions

Table 4: Fixed Effects of the Novel Nonconforming Items Regression

<table>
<thead>
<tr>
<th></th>
<th>Coefficient</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.161</td>
<td>&lt;0.001***</td>
</tr>
<tr>
<td>Trained Contrast Position = final (vs. initial)</td>
<td>0.197</td>
<td>0.522</td>
</tr>
<tr>
<td>Trained Neutralization Value = T (vs. D)</td>
<td>1.063</td>
<td>&lt;0.001***</td>
</tr>
</tbody>
</table>

• Main effect of Trained Contrast Position not significant → no evidence for substantive bias
• Significant main effect of Trained Neutralization Value supports complexity bias

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1 If the interaction of Trained Contrast Position and Trained Neutralization Value is included as a fixed effect in the model, it is not significant (p = 0.208).
2.6 Discussion

- The phonotactic implicational (T/D# → #T/D) was not reproduced in this experiment
  - No greater extension of voicing contrast from word-final to word-initial position
  - **Substantive bias hypothesis not supported**
- Instead, subjects trained to “neutralize” to T extended to D more than subjects trained to “neutralize” to D extended to T
  - Opposite of behavior expected based on relative markedness of T vs. D
  - But given (voiced) sonorant Cs, can be explained by a **complexity bias**
    - #D…{T, D)# (*#T) and #\{T, D\}…D# (*T#) subjects can learn *#[-voice] and *[-voice]#
    - But #T…{T, D)# (*#D) and #\{T, D\}…T# (*D#) subjects must learn more complex
      *#[-son, +voice] and *[-son, +voice]#
  - Complexity bias account depends on English sonorants having active [+voice] feature
  - However, there are other AGL results consistent with complexity bias story for Exp. 1
    (Greenwood 2016, Glewwe et al. 2018)

3. Experiment 2: Modified Voicing Contrast Experiment

3.1 Motivation

- Complexity bias account of Exp. 1: Subjects accepted Novel Nonconforming items less (i.e. learned their language better) when they could use a simpler constraint to master their language
- Which conditions could be learned with simpler constraints depended crucially on features of non-critical Cs of the stimuli, i.e. the voiced sonorants
- To test validity of complexity bias account of Exp. 1, I conducted Exp. 2, which was designed to reverse predictions of complexity bias
- Exp. 2 identical to Exp. 1, except **non-critical Cs converted from voiced sonorants to voiceless fricatives**
- Now it should be easier to learn to reject voiced stops (*D) than to reject voiceless stops (*T)

3.2 Method

- Identical to Exp. 1: Same four training conditions shown in Table 1
- Properties of items (training and test)
  - Identical to Exp. 1, except non-critical Cs (other two Cs in each CVCVC item) drawn from [f θ sʃ h] ([h] only word-initial)

| Table 5: Sample Training Items in the #{T, D}...T# Condition |
|-----|-----|-----|-----|
| #T  | #D  | T#  | D#  |
| pîfîs | bîfîs | fîsîp |  |
| tîʃás | dîʃîθ | fâθît |  |
| kàʃêf | gàʃêf | əfâk |  |
| …   | …   | …   | … |

- Procedure identical to that of Exp. 1

3.3 Participants

- Same population as in Exp. 1
• 144 subjects, divided among 4 conditions (subjects per condition ranged from 35 to 37)

3.4 Predictions

• Like Exp. 1, Exp. 2 still tests for substantive bias, but complexity bias predictions have changed

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Predicted Relative Acceptance Rates of Novel Nonconforming Items by Condition</th>
</tr>
</thead>
</table>

#1 Substantive bias hypothesis (position—Trained Contrast Position):
- Phonotactic implicational: T/D# → #T/D, but not vice versa
- Subjects exposed to contrast word-finally should extend it to word-initial position more than subjects exposed to contrast word-initially extend it to word-final position

#2 Substantive bias hypothesis (voicing—Trained Neutralization Value)
- Voiced stops more marked than voiceless stops → more extension from voiced to voiceless stops than from voiceless to voiced stops

#3 Complexity bias hypothesis:
- Due to presence of voiceless fricatives in training items, constraint needed to exclude Novel Nonconforming items in neutralizing-to-D conditions could be more complex than constraint needed in neutralizing-to-T conditions
  - #\{T, D\}…D# (*T#): túsif ✓ fisib ✓ fisip ✗ → *[−cont, −voice]#
  - #\{T, D\}…T# (*D#): túsif ✓ fisib ✗ fisip ✓ → *[+voice]#

• Predicts more “extension” from voiced to voiceless stops than from voiceless to voiced stops
  - Same prediction as voicing-related Hypothesis #2 above!
  - Exp. 2 cannot disambiguate between voicing-based substantive bias and complexity bias
  - However, Exp. 1 could, and there was no evidence for voicing-based substantive bias
  - Thus I will interpret this pattern of results in Exp. 2 as supporting complexity bias
3.5 Results

- Figure 2 shows the acceptance rates of the three types of test items across conditions:

**Figure 2: Acceptance Rates of Test Items by Condition**

- Acceptance rates of Novel Conforming items:
  - Above chance in all conditions (generalization → learning of trained pattern)
  - Not significantly different across conditions
- Mixed-effects logistic regression fit to Novel Nonconforming items:
  - Dependent variable: response (accept or reject)
  - Fixed effects: Trained Contrast Position and Trained Neutralization Value
  - Random intercepts for subject and item
- Predictions:
  - Position-based substantive bias: Main effect of Trained Contrast Position such that Novel Nonconforming acceptance rates higher in word-final contrast conditions than in word-initial contrast conditions
Complexity bias: Main effect of Trained Neutralization Value such that Novel Nonconforming acceptance rates higher in neutralizing-to-D conditions than in neutralizing-to-T conditions

<table>
<thead>
<tr>
<th>Fixed Effects of the Novel Nonconforming Items Regression²</th>
<th>Coefficient</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.200</td>
<td>&lt;0.001***</td>
</tr>
<tr>
<td>Trained Contrast Position = final (vs. initial)</td>
<td>0.711</td>
<td>0.012*</td>
</tr>
<tr>
<td>Trained Neutralization Value = D (vs. T)</td>
<td>0.522</td>
<td>0.065</td>
</tr>
</tbody>
</table>

- Significant main effect of Trained Contrast Position supports substantive bias
- Marginally significant main effect of Trained Neutralization Value supports complexity bias

3.6 Discussion

- Subjects did behave in accordance with the phonotactic implicational (T/D# → #T/D)
  - Greater extension of voicing contrast from word-final to word-initial position
  - **Supports substantive bias**
- Also, subjects trained to “neutralize” to D extended to T more than subjects trained to “neutralize” to T extended to D
  - Higher acceptance of Novel Nonconforming items in conditions where subjects had to learn *[-cont, –voice] than in conditions where subjects could learn *[+voice]
  - **Consistent with complexity bias**
- Flipping voicing of non-critical Cs flipped direction of differences in Novel Nonconforming acceptance rates between neutralizing-to-T and neutralizing-to-D languages
  - Subjects always better at rejecting Novel Nonconforming items featuring stops whose voicing is opposite that of non-critical Cs
  - Non-critical Cs crucially affect AGL performance
  - Subjects infer phonotactic constraints according to experiment-internal distribution of sounds, opting for simplest constraint with which they can master pattern

4. General Discussion

- Two experiments tested the phonotactic implicational whereby a word-final obstruent voicing contrast entails a word-initial contrast, but not vice versa
  - **Exp. 1:** Natural languages with a stop voicing contrast only word-initially **not reliably learned better than unnatural languages** with a stop voicing contrast only word-finally
  - **Exp. 2:** Natural languages with a stop voicing contrast only word-initially **learned better than unnatural languages** with a stop voicing contrast only word-finally
  - **Mixed evidence for substantive bias**
- What is the outlook for substantive bias?
  - Results of Exp. 1 and 2 in line with Moreton & Pater (2012a,b): substantive bias elusive
  - Typological asymmetries rooted in phonetic naturalness must still be accounted for
  - Substantive bias’s major competitor in this debate: the diachronic explanation/channel bias (Blevins 2004, Moreton 2008)
    - Phonetic factors (e.g. articulatory difficulty, perceptibility) drove imperfect transmission of languages over time, yielding the present typology

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² If the interaction of Trained Contrast Position and Trained Neutralization Value is included as a fixed effect in the model, it is not significant (p = 0.699).
Substantive bias may be subtle/hard to detect, yet notable AGL results exist (Finley 2012, White 2013)

Perhaps a difference between articulatory substantive bias and perceptual substantive bias? (Glewwe et al. 2018)

- In Exps. 1 and 2, position-based substantive bias perceptual while voicing-based substantive bias articulatory, and only position-based substantive bias found any support
- Naturalness arguments in Finley 2012 and White 2013 rooted in perception
- Glewwe et al. 2018: naturalness argument articulatory (final devoicing vs. final voicing) and no evidence for substantive bias

- Both experiments also provided evidence for complexity bias
  - Subjects accepted Novel Nonconforming items less (i.e. demonstrated superior learning) when pattern could be mastered with a featurally simpler phonotactic constraint
  - Effect more consistent and robust across two experiments than substantive bias effect
  - Held true whether simpler conditions were neutralizing-to-D conditions (Exp. 1—sonorant non-critical Cs) or neutralizing-to-T conditions (Exp. 2—voiceless fricative non-critical Cs)
  - Exps. 1 and 2 highlight decisive role non-critical segments/phone inventory of an artificial language can play
  - Interpretations of AGL results must take potential role of non-critical sounds into account

Acknowledgments

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References


