EVIDENCE FOR A LEARNING BIAS AGAINST “SALTATORY” PHONOLOGICAL ALTERNATIONS IN ARTIFICIAL LANGUAGE LEARNING

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Saltatory phonological alternations

- **Saltatory alternation** = alternation in which an intervening sound is “jumped over”

- **Example** from Campidanian Sardinian\(^1\):
  - \(p \rightarrow \beta / V\___\), but \(b\) remains unchanged

  \[
  \begin{align*}
  /\text{pani}/ & \rightarrow [\text{s}:\text{u} \ \beta\text{äi}] \quad \text{‘the bread’} \\
  /\text{binu}/ & \rightarrow [\text{s}:\text{u} \ b\text{ãu}] \quad \text{‘the wine’}
  \end{align*}
  \]

- This is a productive process that occurs at the other places of articulation as well.

1. Bolognesi, 1998
More saltatory alternations

- Some other examples:
  - Colloquial Northern German\(^1\)
    - \(g \rightarrow x / \_\_\#\), \(k\) remains unchanged
  - Polish\(^2\)
    - \(g \rightarrow ʒ / \_\_\ V_{\text{+front}}\), \(ʤ\) remains unchanged
  - Suma (a tonal example)\(^3\)
    - \(L \rightarrow H / H\_\#\) in associative construction, final \(M\) remains unchanged

- Note that these other cases are more limited in nature.

Thus, saltatory alternations are possible, but cross-linguistically rare (at least relative to non-saltatory ones).

Question: Do learners have a bias against learning saltatory alternations?

I will present 4 artificial language experiments with interesting results indicating that they do.
Overview (Experiments 1-4)

- Artificial language learning (n = 20 for all experiments)
- **Basic design strategy**: Withhold certain information during exposure (ambiguous input), then test on the withheld cases to see which assumptions participants make

- Same basic method for Exp 1-4, but types of items in training varies

- 3 phases:
  - Exposure
  - Verification of learning
  - Generalization

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1. E.g., see Wilson, 2006; Finley, 2008; and others
Experiment 1 - Method

- Artificial language learning (Auditory)
- **Exposure phase:** Train on $p \rightarrow v$, $t \rightarrow \delta$ / V__V
Experiment 1

- Artificial language learning (Auditory)
- Exposure phase: Train on p \( \rightarrow \) v, t \( \rightarrow \) ð / V__V
Experiment 1

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"lanap"
Experiment 1

- Artificial language learning (Auditory)
- **Exposure phase**: Train on p $\rightarrow$ v, t $\rightarrow$ ď / V__V
Experiment 1

- Artificial language learning (Auditory)
- Exposure phase: Train on p → v, t → ð / V__V

“lanavi”
Experiment 1

- **Exposure phase**: Train on $p \rightarrow v, t \rightarrow \delta / V__V$
  - All singular words are CVCVC, sound inventory drawn from a subset of English phonemes
  - 36 changing items ending in /p/ or /t/
    - lanap ~ lanavi (18 of this type)
    - bunat ~ bunaði (18 of this type)
  - 36 non-changing Filler items
    - Ending in /m, n, l, r, s, sʃ/
    - Example: kasam ~ kasami
- Crucially, no words ending in intervening /b, d, f, θ/
Experiment 1

- **Verification phase**: Did they learn the pattern?
- **Task**: Hear a previously heard singular form and choose the correct plural form
  - 2-alternative forced choice test → Choose between two options: *changing* and *non-changing*.
  - 32 words from Exposure phase (8 p, 8 t, 16 fillers)
  - Must get at least 80% to move on — so that I know they have learned the pattern
Experiment 1

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“lanap”
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- **Task:** Hear a previously heard singular form and choose the correct plural form

“lanapi”...“lanavi”

???????????????
Experiment 1

- **Verification phase:** Did they learn the pattern?
- **Task:** Hear a previously heard singular form and choose the correct plural form

Note: Changing option for fillers:
/m, r,伸/ → 严肃 (kasami ... kasavi)
/n, l, s/ → δ

“lanapi”...“lanavi”

???????????????
Experiment 1 - Method

- **Generalization phase:** Same task as verification phase, but with **novel words**.
  - 24 words ending in /p, t/
  - 24 fillers
  - But **crucially** also 24 words ending in the untrained, intervening sounds /b, d, f, θ/
Experiment 1

Input: \( p \rightarrow v \rightarrow t \rightarrow \delta \)

Possible interpretations of input: (Coronals analogous)

- Saltatory
- Partially saltatory
- Non-saltatory
Experiment 1 – Results (all words are novel)

![Bar graph showing mean percentage change in option chosen for trained and untrained sounds]

- **Trained sounds**
  - p, t
  - Fillers
  - b, d
  - f, θ

- **Untrained sounds**

**Final sound of singular word**

- Mean % changing option chosen
Experiment 1 – Results (all words are novel)

E.g., for a word like lanap, how frequently did participants choose lanavi rather than lanapi?
Experiment 1 – Results (all words are novel)

Participants learned pattern and extended it to new forms of the same type.
Experiment 1 – Results (all words are novel)

Participants generalized to intervening sounds at a high rate, even with no evidence for such a change!
Experiment 1 – Results (all words are novel)

Participants generalized to intervening sounds at a high rate, even with no evidence for such a change.
Experiment 1 – Results (all words are novel)

Greater change for intervening stops than for fricatives!
Observations so far

- Given ambiguous input, learners generalize to make learned alternations non-saltatory.

- There is a preference towards changing voiced stops more than voiceless fricatives.
  - Binary abstract features cannot account for this difference
  - Perhaps perceptual similarity is important

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<thead>
<tr>
<th></th>
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<tr>
<td>Labials</td>
<td>b ~ v</td>
<td>0.153</td>
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<tr>
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<td>f ~ v</td>
<td>0.039</td>
</tr>
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<td>Coronals</td>
<td>d ~ ð</td>
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1. Wang & Bilger, 1973

= avg. of (rate that b is mistaken for v and rate that v is mistaken for b) (from confusion matrix data)
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Indeed, voiced stops \([b, d]\) are more confusable with voiced fricative targets \([v, ʕ]\) than voiceless fricatives \([f, \theta]\).
Two alternate explanations

- They just learned a more general rule: all stops become voiced fricatives between vowels

- Product-oriented responses:¹ a large number of [-vi] and [-ði] plural endings resulted in a bias towards choosing those endings for new cases
  - ½ of the plurals ended in [-vi] or [-ði]
  - 1/12 ended in each of [-mi], [-ni], [-li], [-ri], [-si], [-ʃi]

2. Bybee & Slobin, 1982
Train on b $\rightarrow$ v and d $\rightarrow$ δ, withhold p, t, f, θ.

- Designed to address alternate explanations:
  - If learning a more general rule or responding based on product-oriented schema, then effect should remain.
  - If it is really something about the intervening sound, then the effect should be greatly reduced.
Experiment 2 - Control

Input:

\[
\begin{align*}
&b \\
&v
\end{align*}
\]

Expected behavior:

\[
\begin{align*}
p &\rightarrow b & p &\rightarrow b & p &\rightarrow b & p &\rightarrow b \\
&\rightarrow v & &\rightarrow v & &\rightarrow v & &\rightarrow v \\
&\rightarrow \phi & &\rightarrow \phi & &\rightarrow \phi & &\rightarrow \phi \\
\text{(Coronals analogous)}
\end{align*}
\]

More general rule (Similar to Exp 1)

Product-oriented responses (Similar to Exp 1)

Bias against saltations (Different from Exp 1)
Experiment 2 - Control

Input:

Expected behavior:

More general rule (Similar to Exp 1)

Bias against saltations (Different from Exp 1)

Product-oriented responses (Similar to Exp 1)

Little generalization to other sounds
Experiment 2 – Results

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<tr>
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<th>Exp 1</th>
<th>Exp 2: Control</th>
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<tbody>
<tr>
<td>Trained stops</td>
<td>90%</td>
<td>80%</td>
</tr>
<tr>
<td>Fillers</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>Untrained stops</td>
<td>70%</td>
<td>20%</td>
</tr>
<tr>
<td>Untrained fricatives</td>
<td>50%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Mean % changing option chosen

Final sound of singular word
Experiment 2 – Results

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</tr>
<tr>
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<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Untrained fricatives</td>
<td>30</td>
<td>20</td>
</tr>
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Exp 1: Learned trained pattern equally well.

Final sound of singular word

Learned trained pattern equally well.
Experiment 2 – Results

Trained sounds

Untrained sounds

Mean % changing option chosen

Trained stops | Fillers | Untrained stops | Untrained fricatives

Exp 1 | Exp 2: Control

Final sound of singular word

Untrained generalization enormously reduced!
Experiment 2 – Results

2 x 2 ANOVA: Sig. main effect of Exp for untrained sounds (Type x Exp)
Experiment 2 – Results

Still sig. different than trained fillers → can think of this as the basic effect of being trained vs. untrained
Observations so far

- Given ambiguous input, learners generalize to make learned alternations non-saltatory.
  - This effect cannot be explained by participants learning a general rule or by product-oriented responses.
- There is a preference towards changing voiced stops more than voiceless fricatives.
  - Binary abstract features cannot account for this difference
  - Perhaps perceptual similarity is important
Experiment 3 – Blocked stops

- Train participants on $p \rightarrow v$ and $t \rightarrow \delta$, but also that $b$ and $d$ do not change

- In training:
  - 18 $p \rightarrow v$
  - 18 $t \rightarrow \delta$
  - 18 non-changing $b$, $d$ (9 of each)
  - 18 non-changing fillers
  - Nothing about $f$, $\theta$

Input: $p \rightarrow b \rightarrow f \rightarrow v$

(Coronals analogous)
Experiment 3 – Blocked stops

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- In training:
  - 18 $p \rightarrow v$
  - 18 $t \rightarrow \delta$
  - 18 non-changing $b$, $d$ (9 of each)
  - 18 non-changing fillers
  - Nothing about $f$, $\theta$

Equal # of non-changing fillers and non-changing $b$, $d$

Input: $p \rightarrow b \rightarrow f \rightarrow v$

(Coronals analogous)
Experiment 3 – Blocked stops

- **Prediction:** If there is bias against saltatory alternations
  - % changing option for fricatives /f, θ/ should remain high

Input: (Coronals analogous)
Experiment 3 – Results

Trained Sounds

Untrained or Blocked Sounds

Mean % changing option chosen

Exp 1
Exp 2: Control
Exp 3: Blocked stops

Trained stops
Fillers
Untrained/Blocked stops
Untrained fricatives

Final sound of singular word
Experiment 3 – Results

Learned trained pattern equally well
Experiment 3 – Results

No difference in generalization to untrained fricatives between Exp 1 and Exp 3
Experiment 3 – Results

Trained Sounds

Untrained or Blocked Sounds

Exp 1
Exp 2: Control
Exp 3: Blocked stops

Sig. more mistakes on blocked stops than on fillers despite being trained to not change stops!
Experiment 3 – Results

**Trained Sounds**

- **Exp 1**
- **Exp 2: Control**
- **Exp 3: Blocked stops**

**Untrained or Blocked Sounds**

- **Exp 1**
- **Exp 2: Control**
- **Exp 3: Blocked stops**

**Final sound of singular word**

- **Trained stops**
- **Fillers**
- **Untrained/Blocked stops**
- **Untrained fricatives**

Equal to Exp 2 even though Exp 3 is trained and Exp 2 is untrained!
Experiment 4 – Blocked Fricatives

- Same as Exp 3, but the fricatives are blocked instead of the stops
- Will we see the same pattern?

Input: p b (Coronals analogous)
Experiment 4 – Results

Trained Sounds

<table>
<thead>
<tr>
<th>Final sound of singular word</th>
<th>Trained stops</th>
<th>Fillers</th>
<th>Untrained/Blocked stops</th>
<th>Untrained/Blocked frics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 1</td>
<td>Blue</td>
<td>Orange</td>
<td>Green</td>
<td>Purple</td>
</tr>
<tr>
<td>Exp 2: Control</td>
<td>Brown</td>
<td>Green</td>
<td>Orange</td>
<td>Purple</td>
</tr>
<tr>
<td>Exp 3: Blocked stops</td>
<td>Green</td>
<td>Purple</td>
<td>Orange</td>
<td>Brown</td>
</tr>
<tr>
<td>Exp 4: Blocked frics</td>
<td>Orange</td>
<td>Brown</td>
<td>Green</td>
<td>Purple</td>
</tr>
</tbody>
</table>

Untrained or Blocked Sounds

- Trained Sounds
- Untrained/Blocked Sounds

Mean % changing option chosen

Final sound of singular word

Graph showing the results of different experimental conditions.
Experiment 4 – Results

Learned trained pattern equally well
Experiment 4 – Results

![Graph showing results](image)

- **Trained Sounds**
  - Exp 1: Mean % changing option chosen
  - Exp 2: Control
  - Exp 3: Blocked stops
  - Exp 4: Blocked frics

- **Untrained or Blocked Sounds**
  - Untrained stops equal to Exp 1
  - Trained sounds compared
Experiment 4 – Results

Sig. more errors on blocked frics than on fillers despite being trained to not change frics!
Experiment 4 – Results

Greater than Exp 2 even though Exp 4 is trained and Exp 2 is untrained!
Observations so far

- Given ambiguous input, learners generalize to make learned alternations non-saltatory.
  - This effect cannot be explained by participants learning a general rule or by product-oriented responses.
- There is a preference towards changing voiced stops more than voiceless fricatives.
  - Binary abstract features cannot account for this difference.
  - Perhaps perceptual similarity is important.
- Even when learners are trained that intervening sounds should not change, they have a tendency to change them to make the alternation non-saltatory.
Theoretical Implications

What do we know?
What do we know?

- Natural languages exist with saltatory alternations.
  - So phonological theory must be able to generate grammars that allow saltatory alternations.
  - Even this is not totally straightforward (e.g., classical OT\(^1\) cannot handle them).

1. Prince & Smolensky, 1993/2004
Theoretical Implications

What do we know?

- Natural languages exist with saltatory alternations.
  - So phonological theory must be able to generate grammars that allow saltatory alternations.
  - Even this is not totally straightforward (e.g., standard OT cannot handle them).
- Saltatory alternations are relatively rare and I have shown that learners are biased against learning a system containing them.
  - So our theories of phonological learning should account for why these alternations are dispreferred in learning.

1. Prince & Smolensky, 1993/2004
Nature of the bias

- Substantive bias
  - Steriade’s P-map principle seems to be a good basis for such a bias in this case (at least for a starting point)
    - P(erceptual)-map → Humans are aware of perceptual relationships between sounds (in a given context) and alternations should minimize perceptual changes
    - Accounts for a preference for short distance changes over long distance changes
    - Also accounts nicely for the preference in Exp 1 to change b → v more than f → v (b is more perceptually similar to v).

1. E.g., Wilson, 2006; Finley & Badecker, 2008; etc.  
2. Steriade 2001/2008
Nature of the bias

- Preliminary computational modeling looks promising for the P-map:
  - Maximum Entropy grammar learning\(^1\) with weighted constraints banning relevant alternating pairs (e.g., \(*p\sim v*)
  - Input/test items based on experiments
  - With a prior (= bias) based on the P-map, the model does pretty well; the unbiased model fails

- Is P-map sufficient?
  - Further experiments/modeling will help determine whether something else has a role (e.g., general dispreference for saltation that is more than just perceptual distance)

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Future directions

- More computational modeling
  - Will help explore what types of biases work and make predictions for additional experiments

- Open response/production experiments

- Infant study
  - Do infants display a bias against saltation when learning phonological alternations?
  - Will help determine if this bias is operational in child language acquisition
Conclusions

- Learners are biased against learning saltatory alternations.
  - When trained on alternations that are (potentially) saltatory, they make assumptions/errors that make them not saltatory.
- Perceptual similarity appears to play a role in this bias.
- A substantive bias based on the P-map seems like a promising starting point for modeling the effect.
Thank you!

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References


