Computational accounts of human learning bias: Implications for locality in ABC

Kevin McMullin
Department of Linguistics
University of British Columbia

ABC↔C: Conference on Agreement by Correspondence
University of California, Berkeley
May 18, 2014
Formal/computational language theory

- The Chomsky Hierarchy (Chomsky 1956)
  - A way to determine the computational complexity of a language or linguistic pattern, based on the type of grammar that generates it
Formal/computational language theory

- Virtually all phonological patterns are regular relations (Johnson 1972; Kaplan and Kay 1994)
  - Mappings that can be described as ordered rewrite rules
- Any stringsets generated by these relations are also regular (Rabin and Scott 1959)
  - Surface phonotactics
A learnability problem

- **Hypothesis**: Humans can learn the class of regular languages
  - Definition of learnability (Gold 1967): *Exact identification in the limit from positive data*
- **Gold’s Theorem** (Gold 1967)
  - Proof that language classes with a certain property are not learnable for any one learning algorithm
- **Problem**: The regular region is one of these language classes
  - There is no one learner for which the entire class of regular languages is learnable

This cannot be the learner’s hypothesis space
The approach

- Relaxing the definition of learnability does not help
  - **Exact** identification...
    - The regular class is not learnable even in a Probably Approximately Correct framework (Valiant 1984)
  - ...in the **limit**...
    - There is a finite number of input strings for human learners
  - ...from **positive** data
    - The idea that children have access to negative data is controversial (Marcus 1993)
    - Holds for all learners, even those that use negative evidence (Johnson 2004)

- **Possible solution**: Restrict the learner’s hypothesis space
  - Not all regular patterns are found in natural language
  - Perhaps the learner’s hypothesis space is a well-defined subset of the regular languages
Restricting the hypothesis space

- Optimality Theory
  - Hypothesis space is limited to the ranking permutations (a factorial typology) of universal constraints (learning biases)
- Formal language theory
  - All attested phonotactic patterns should be formally described as a learnable class of languages

![Diagram showing the relationship between regular languages, a factorial typology of OT constraints, a learnable class of formal languages, and the hypothesis space.](diagram.png)
Summary of today’s argument

1. Experimental studies reveal human learning biases that reflect the typology of locality in non-adjacent consonant interaction

2. Accounts of these learning biases and the typology exist within phonological theory (Agreement by Correspondence) and formal language theory (the Subregular Hierarchy)

3. The two approaches are incompatible, as they predict different sets of learnable languages with respect to the possible locality parameters of long-distance dependencies
## Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consonant harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consonant dissimilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- Long-distance dissimilation in the subregular hierarchy
- A factorial typology of ABC constraints for dissimilation (and harmony)
- Experimental results for studies of consonant dissimilation
- Sketching out the problem and discussing possible solutions
# Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consonant harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consonant dissimilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- Long-distance dissimilation in the subregular hierarchy
- A factorial typology of ABC constraints for dissimilation (and harmony)
- Experimental results for studies of consonant dissimilation
- Sketching out the problem and discussing possible solutions
Harmony: Two types of locality
(Hansson 2001, 2010a; Rose and Walker 2004)

• **UNBOUNDED** – holds at any distance
  • Example: Yaka nasal consonant harmony (Hyman 1995)
    - tsúb-idi ‘wander-PFV’
    - tsúm-ini ‘sew-PFV’
    - mí:tuk-ini ‘sulk-PFV’

• **TRANSVOCALIC** – holds across at most one vowel (CvC sequences)
  • Example: Lamba nasal consonant harmony (Odden 1994)
    - pat-ile ‘scold-PFV’
    - u:m-ine ‘dry-PFV’
    - mas-ile ‘plaster-PFV’

• **Hypothesis**: This dichotomy reflects a human learning bias
Artificial language learning: Methodology

• An experimental method for studying linguistic learning
  • See Moreton and Pater (2012a,b) for a recent review
• Participants are trained on a controlled miniature language
  • The language contains some pattern of interest
    • e.g., Consonant harmony
• Participants can be tested on
  • Whether or not (or how well/quickly) they learn the pattern
  • Whether they generalize the pattern to novel contexts

• Many recent studies present evidence in support of a relationship between typology and learning bias
  • See Rafferty, Griffiths, and Ettlinger (2013) for limitations
Artificial language learning: Experiments

• Finley (2011, 2012)
  • Root-to-suffix sibilant harmony
  • Learners do not generalize cv$\ddot{s}$v-Sv harmony to Svcv-Sv
  • Learners do generalize cv$\ddot{S}$vcv-Sv, both to cvcv$\ddot{S}$v-Sv and Svvcvcv-Sv

• McMullin (2013)
  • Replicates result with suffix-to-root sibilant harmony

• Sibilant harmony in the absence of other information
  • ...$S_vS...$ learned as a transvocalic dependency
  • ...$S_{vcv}S...$ learned as a truly unbounded dependency
Liquid harmony experiment: Training
(McMullin and Hansson 2013)

• 3 training conditions (12 subjects in each group)
  • Short-range (...Lv-Lv), Medium-range (...Lvcv-Lv), Control (cvcvcv-Lv)

• Suffix liquids (-ru,-li) trigger root alternations resulting in harmony
• Training triplets: root followed by two suffixed forms
• 4 speakers

• Example of medium range training below
  • ...{pilede...pilede-li...pirede-ru}...
  • ...{nelogi...nerogi-ru...nelogi-li}...
  • ...{kurupe...kolupe-li...kurupe-ru}...
  • ...{torite...torite-ru...tolite-li}...
Liquid harmony experiment: Testing
(McMullin and Hansson 2013)

• 2AFC testing at three levels of locality
  • Short- (cvcvLv-Lv), Medium- (cvLvcv-Lv), and Long-range (Lvcvcv-Lv)

• Testing trials: root followed by two options with the same suffix
  • {pidole...pidole-ru/pidore-ru} (Short-range)
  • {tuluge...tuluge-li/turuge-li} (Medium-range)
  • {romuge...lomuge-li/romuge-li} (Long-range)

• Do learners choose the option with harmony at each distance?
Results: Liquid harmony (Restricted training)

(McMullin and Hansson 2013)
Typology and learning bias

- This result reflects the typology of consonant harmony
  - Two types of locality, transvocalic and unbounded

<table>
<thead>
<tr>
<th></th>
<th>...Cv-Cv</th>
<th>...Cvcv-Cv</th>
<th>Cvcvcv-Cv</th>
</tr>
</thead>
<tbody>
<tr>
<td>transvocalic</td>
<td>+</td>
<td>×</td>
<td>−</td>
</tr>
<tr>
<td>unbounded</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>unattested</td>
<td>−</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>unattested</td>
<td>+</td>
<td>×</td>
<td>+</td>
</tr>
<tr>
<td>unattested</td>
<td>−</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

- Accounting for this dichotomy/learning bias in OT
  - Universal ABC constraints only allow for these two locality levels
Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consonant harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consonant dissimilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- Long-distance dissimilation in the subregular hierarchy
- A factorial typology of ABC constraints for dissimilation (and harmony)
- Experimental results for studies of consonant dissimilation
- Sketching out the problem and discussing possible solutions
Harmony in ABC
(Bennett 2013; Hansson 2001, 2010a; Rose and Walker 2004)

• Input-Output faithfulness constraints
  • e.g., IDENT[son]-IO, IDENT[voi]-IO

• Correspondence constraints:
  • Require certain sets of segments to be in correspondence
    • CORR[X←→Y], CORR[G], or CORR[αG] (e.g., CORR[-son])
  • ‘CC·Limiter’ constraints (Bennett 2013) that impose restrictions
    on correspondents
    • IDENT-CC constraints
      • Require correspondents to agree in some feature
      • IDENT[F]-CC (e.g. IDENT[voi]-CC)
    • Locality constraints
      • PROXIMITY or CC·SYLLADJ (I will use cvc-CC)
      • Correspondents must be in a CVC relationship (i.e. Short-range)
Unbounded harmony

- Hypothetical language with **obstruent voicing harmony**

<table>
<thead>
<tr>
<th>(…CvC…)</th>
<th>/lapaba/</th>
<th>IDENT [son]-IO</th>
<th>CORR [-son]</th>
<th>IDENT [voi]-CC</th>
<th>IDENT [voi]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faithful</td>
<td>a. lap_xab_ya</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. lap_xab_xa</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmony</td>
<td>c. lap_xap_xa</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Dissimilation</td>
<td>d. lap_xam_ya</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(…CvcvC…)</th>
<th>/palaba/</th>
<th>IDENT [son]-IO</th>
<th>CORR [-son]</th>
<th>IDENT [voi]-CC</th>
<th>IDENT [voi]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faithful</td>
<td>a. p_xalab_ya</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Faithful</td>
<td>b. p_xalab_xa</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Harmony</td>
<td>c. p_xalap_xa</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Dissimilation</td>
<td>d. p_xalam_ya</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>
Transvocalic harmony

- Same language but with a **high-ranked cvc-CC constraint**

<table>
<thead>
<tr>
<th></th>
<th>cvc-CC</th>
<th>IDENT [son]-IO</th>
<th>CORR [-son]</th>
<th>IDENT [voi]-CC</th>
<th>IDENT [voi]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>(...CvC...)</td>
<td>/lapaba/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>a. lap_xab_ya</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. lap_xab_xa</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Harmony</td>
<td>c. lap_xap_xa</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Dissimilation</td>
<td>d. lap_xam_ya</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>cvc-CC</th>
<th>IDENT [son]-IO</th>
<th>CORR [-son]</th>
<th>IDENT [voi]-CC</th>
<th>IDENT [voi]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>(...CvcvC...)</td>
<td>/palaba/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>a. p_xalab_ya</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. p_xalab_xa</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Harmony</td>
<td>c. p_xalap_xa</td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Dissimilation</td>
<td>d. p_xalam_ya</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The OT account of...

- **Typology**
  - Ranking permutations of harmony using CVCC-CC include:
    - Unbounded harmony (low-ranked CVCC-CC)
    - Transvocalic harmony (high-ranked CVCC-CC)

- **Learnability**
  - Innate constraints are learning biases
    - CVCC-CC: short-range dependencies are different
  - Constraint rankings are learned with a re-ranking algorithm
    - The learner can only arrive at these two types of harmony
  - Should another type of locality arise...
    - It would not be learned by a new generation of speakers OR
    - It would be over-/under-generalized
Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consonant harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consonant dissimilation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- Long-distance dissimilation in the subregular hierarchy
- A factorial typology of ABC constraints for dissimilation (and harmony)
- Experimental results for studies of consonant dissimilation
- Sketching out the problem and discussing possible solutions
The subregular hierarchy
(McNaughton and Papert 1971)

- Not all regular languages are attested as phonotactic patterns
- Instead, consider a proper subset of the regular region
  - We know a lot about the formal properties of some subregular classes
    (See e.g., Heinz 2010; Heinz, Rawal, and Tanner 2011; Rogers and Pullum 2011)
- Can we define a demand for agreement within one of these subregular classes of formal languages?

(Adapted from Heinz et al. 2011)
Strictly $k$-Local languages ($SL_k$)
(Heinz 2010)

- Bounded co-occurrence restrictions (up to length $k$)
  - $SL_2$ patterns are adjacent co-occurrence restrictions
    - *CC, *bm, *h#
  - $SL_3$ patterns restrict the set of possible trigrams
    - Transvocalic harmony can be described as $SL_3$
    - *sij, *jas (but sV...Vj words are not ruled out)

- $SL$ languages are learnable (Heinz 2010)
  - With an algorithm that records all encountered $k$-factors ($n$-grams)
  - The grammar is a set of all permitted $k$-factors (equivalently, all prohibited $k$-factors)
    - e.g. \{*lVj, *jVI\} is a grammar for transvocalic liquid harmony

- **Unbounded harmony is not $SL_k$**
  - The dependency holds even at length $k+1
Strictly $k$-Piecewise languages ($\text{SP}_k$) (Heinz 2010)

- Unbounded co-occurrence restrictions
  - $\text{SP}_2$ patterns prohibit $x...y$ subsequences
  - **Unbounded harmony can be described as** $\text{SP}_2 (\ast s...\ast, \ast \ast...s)$

- $\text{SP}$ languages are learnable (Heinz 2010)
  - With an algorithm that records all encountered $k$-subsequences
    - ‘abcd’ $\rightarrow$ \{a...b, a...c, a...d, b...c, b...d, c...d\}
  - The grammar is a set of permitted (prohibited) subsequences
    - \{\ast \ast...\ast, \ast \ast...\ast\} for unbounded liquid harmony
A modular account of learning bias

- McMullin and Hansson (2013) argue that a modular learner accounts for the typology and observed learning bias
  (For more on modular approaches to learning, see Heinz 2010; Heinz and IJsards 2011; Lai 2012)
  - Learners use a SL₃ learning algorithm for transvocalic harmony
    - This happens first for experimental learners (no generalization)
  - Learners use a SP₂ learning algorithm for unbounded harmony
### Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consonant harmony</td>
<td>2.</td>
<td>3.</td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td>5.</td>
<td></td>
</tr>
<tr>
<td>Consonant dissimilation</td>
<td>6.</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- **Everything looks good so far**
- Long-distance dissimilation in the subregular hierarchy
- A factorial typology of ABC constraints for dissimilation (and harmony)
- Experimental results for studies of consonant dissimilation
- Sketching out the problem and discussing possible solutions
### Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- **Long-distance dissimilation in the subregular hierarchy**
  - A factorial typology of ABC constraints for dissimilation (and harmony)
  - Experimental results for studies of consonant dissimilation
  - Sketching out the problem and discussing possible solutions
Evidence against a SL+SP hypothesis space

- Dissimilation with blocking is attested
  - Example: Latin liquid dissimilation (Jensen 1974; Odden 1994)
    - /lun-aǐs/ → [lun-aandbox]
      *l...l is prohibited
    - /flɔr-aǐs/ → [flɔr-aandbox] *[flɔr-aandbox] l...l if [r] intervenes
  - Unbounded dependencies with blocking are not SP (or SL)

- Long-distance dissimilation motivates a new approach for defining a language learner’s hypothesis space
Evidence against a SL+SP hypothesis space

- **Unbounded dependencies with blocking are not SP** (or SL)
  - This includes dissimilation as well as harmony
- Heinz (2010) argues that this is desirable when describing unbounded consonant harmony as SP
  - Based on a lack of attested systems exhibiting blocking effects (Hansson 2001; Rose and Walker 2004)
- Some harmony systems are now thought to exhibit blocking
  - Some Berber dialects (Elmedlaoui 1995; Hansson 2010b)
  - Kinyarwanda (Walker and Mpiranya 2006)
  - Slovenian (Jurgec 2011)
A tier-based description of blocking

• Latin liquid dissimilation can be described as $SL_2$, if locality (adjacency) is assessed only with respect to other liquids
  • /lun-almis/ $\rightarrow$ [lun-aris] is now:       /ll/ $\rightarrow$ [lr]
  • /flor-alis/ $\rightarrow$ [flor-alis] is now:       /lrl/ $\rightarrow$ [lrl]

• This is more like a Strictly Local pattern
  • The grammar prohibits {*ll} on the liquid tier
  • [lrl] does not violate these restrictions, since [lr], [rl] are permitted

• Long-distance dissimilation with blocking is a member of the Tier-based Strictly Local class (Heinz et al. 2011)
Tier-based Strictly Local languages (TSL) (Heinz 2010)

- Tiers (projections, subsequences) can be defined with:
  - Features, natural classes, arbitrary subsets of the inventory
- Example strings for tiers in a hypothetical word ‘pi̞ejaʃolu’:
  - Vowel tier – ieau
  - Consonant tier – puʃʃl
  - Sibilant tier – ŋ
  - Liquid tier – ɬ
  - {ŋ,p,i,u} tier – piʃʃu

- **Hypothesis**: A language is a possible (human-learnable) language if and only if it is TSL$_{(k?)}$
  - Some evidence of learnability of long-distance dependencies on arbitrarily defined tiers (Koo and Oh 2013)
A TSL$_2$ account of the locality dichotomy

- Consonant harmony is just agreement on different tiers
- Transvocalic dependencies are TSL$_2$ on the consonant tier
  - *tasaf $\{ts, *s\}$
  - *sataf $\{st, tf\}$
- Unbounded dependencies are TSL$_2$ on the sibilant tier
  - *tasaf $\{*s\}$
  - *sataf $\{*s\}$
- These are no longer different locality parameters, just adjacency amongst a different set of segments

- Harmony with blocking is TSL$_2$ on the coronal tier
  - *sapaaf $\{*s\}$
  - *sataf $\{st, tf\}$
Locality patterns that are not TSL$_2$

- First-last harmony (Locally Testable; Lai 2012)
  - *#s...(ʃ)...(s)...ʃ# not learned in experimental studies
- Dependencies that hold across exactly two vowels (TSL$_3$)
  - $sVʃ, *sVCVʃ, sV...V...Vʃ$ (unattested)
- Dependencies that hold across at most two vowels (TSL$_3$)
  - $*sVʃ, *sVCVʃ, sV...V...Vʃ$ (unattested)

- Dependencies that hold only across at least two vowels
  - $sVʃ$ is permitted, but $*sV...Vʃ$ (*medium- and long-range)
    - Locally Testable for harmony
    - Locally Threshold Testable for dissimilation
Advantages of the TSL approach

• TSL languages seem to reflect the typology of consonant harmony and dissimilation
  • Both attested and unattested patterns

• They are defined in the framework of formal language theory
  • Easy to study their computational properties and learnability

• They are not incompatible with phonological theory (features, violable constraints, etc.)
A challenge for the TSL approach

- Is the TSL class learnable?
  - Yes, if the learner knows the tier \textit{a priori} (Heinz et al. 2011)
  - It is an open question whether there is an algorithm that can learn a TSL pattern on any unknown tier (or multiple tiers)
  - Can humans navigate this hypothesis space efficiently?
    - Perhaps only for certain phonologically well-defined tiers
- TSL languages describe \textit{phonotactic} patterns
  - Is there an analogous way to discuss phonological mappings?
### Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consonant harmony</td>
<td>2.</td>
<td></td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td>3.</td>
<td></td>
</tr>
<tr>
<td>Consonant dissimilation</td>
<td>5.</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- Long-distance dissimilation in the subregular hierarchy
- **A factorial typology of ABC constraints for dissimilation (and harmony)**
- Experimental results for studies of consonant dissimilation
- Sketching out the problem and discussing possible solutions
**Dissimilation: Unbounded**

- Unbounded dissimilation with low-ranked [son] faithfulness
- Surface correspondence theory of dissimilation (Bennett 2013)

<table>
<thead>
<tr>
<th>(...CvC...)</th>
<th>/lapaba/</th>
<th>IDENT [voi]-IO</th>
<th>CORR [-son]</th>
<th>IDENT [voi]-CC</th>
<th>CVC-CC</th>
<th>IDENT [son]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faithful</td>
<td>a. lapₙabᵧa</td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. lapₙabₓa</td>
<td></td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmony</td>
<td>c. lapₓapₓa</td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissimilation</td>
<td>☞ d. lapₓamᵧa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(...CvcvC...)</th>
<th>/palaba/</th>
<th>IDENT [voi]-IO</th>
<th>CORR [-son]</th>
<th>IDENT [voi]-CC</th>
<th>CVC-CC</th>
<th>IDENT [son]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faithful</td>
<td>a. pₓalabᵧa</td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. pₓalabₓa</td>
<td></td>
<td></td>
<td>*!</td>
<td>*(!)</td>
<td></td>
</tr>
<tr>
<td>Harmony</td>
<td>c. pₓalapₓa</td>
<td>*!</td>
<td></td>
<td></td>
<td>*(!)</td>
<td></td>
</tr>
<tr>
<td>Dissimilation</td>
<td>☞ d. pₓalamᵧa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>
# Dissimilation: Unbounded

- Note: **Identical consonants** will not dissipilate at \( \text{CvC} \) locality
- Nothing forces them out of correspondence

<table>
<thead>
<tr>
<th>( \ldots \text{CvC...} )</th>
<th>( /ababa/ )</th>
<th>IDENT [\text{voi}]-IO</th>
<th>CORR [-\text{son}]</th>
<th>IDENT [\text{voi}]-CC</th>
<th>( \text{CVC-CC} )</th>
<th>IDENT [\text{son}]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faithful</td>
<td>a. ( \text{lab}_x \text{ab}_y \text{a} )</td>
<td></td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. ( \text{lab}_x \text{ab}_x \text{a} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmony</td>
<td>c. ( \text{lab}_x \text{ab}_x \text{a} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissimilation</td>
<td>d. ( \text{lab}_x \text{am}_y \text{a} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \ldots \text{CvcvC...} )</th>
<th>( /balaba/ )</th>
<th>IDENT [\text{voi}]-IO</th>
<th>CORR [-\text{son}]</th>
<th>IDENT [\text{voi}]-CC</th>
<th>( \text{CVC-CC} )</th>
<th>IDENT [\text{son}]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faithful</td>
<td>a. ( \text{b}_x \text{alab}_y \text{a} )</td>
<td></td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. ( \text{b}_x \text{alab}_x \text{a} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*!</td>
</tr>
<tr>
<td>Harmony</td>
<td>c. ( \text{b}_x \text{alab}_x \text{a} )</td>
<td></td>
<td></td>
<td></td>
<td>*!</td>
<td></td>
</tr>
<tr>
<td>Dissimilation</td>
<td>d. ( \text{b}_x \text{alam}_y \text{a} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>
**Dissimilation: Transvocalic**

- Transvocalic dissimilation impossible with only these constraints
- Dissimilation will win at all locality levels

<table>
<thead>
<tr>
<th></th>
<th>/lapaba/</th>
<th>IDENT [voi]-IO</th>
<th>CORR [-son]</th>
<th>IDENT [voi]-CC</th>
<th>CVC-CC</th>
<th>IDENT [son]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faithful</td>
<td>a. lap_xab_ya</td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. lap_xab_xa</td>
<td></td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmony</td>
<td>c. lap_xap_xa</td>
<td>*!</td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissimilation</td>
<td>d. lap_xam_ya</td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>/palaba/</th>
<th>IDENT [voi]-IO</th>
<th>CORR [-son]</th>
<th>IDENT [voi]-CC</th>
<th>CVC-CC</th>
<th>IDENT [son]-IO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faithful</td>
<td>a. p_xalab_ya</td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faithful</td>
<td>b. p_xalab_xa</td>
<td></td>
<td></td>
<td>*!</td>
<td>*(!)</td>
<td></td>
</tr>
<tr>
<td>Harmony</td>
<td>c. p_xalap_xa</td>
<td>*!</td>
<td></td>
<td></td>
<td>*(!)</td>
<td></td>
</tr>
<tr>
<td>Dissimilation</td>
<td>d. p_xalam_ya</td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>
Dissimilation: Beyond-transvocalic

- ...Cv...vC... dissimilation, but faithfulness/harmony at ...CvC...
- Sundanese liquid dependencies are one possible case (Bennett 2013)

<table>
<thead>
<tr>
<th></th>
<th>/lapaba/</th>
<th>CVC-CC</th>
<th>CORR [son]</th>
<th>IDENT [son]-IO</th>
<th>IDENT [voi]-IO</th>
<th>IDENT [voi]-CC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Faithful</strong></td>
<td>a. lap\textsubscript{x}ab\textsubscript{y}a</td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Faithful</strong></td>
<td>b. lap\textsubscript{x}ab\textsubscript{a}a</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Harmony</strong></td>
<td>c. lap\textsubscript{x}ap\textsubscript{a}a</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td><strong>Dissimilation</strong></td>
<td>d. lap\textsubscript{x}am\textsubscript{y}a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>/palaba/</th>
<th>CVC-CC</th>
<th>CORR [son]</th>
<th>IDENT [son]-IO</th>
<th>IDENT [voi]-IO</th>
<th>IDENT [voi]-CC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Faithful</strong></td>
<td>a. p\textsubscript{x}alab\textsubscript{y}a</td>
<td></td>
<td>*!</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Faithful</strong></td>
<td>b. p\textsubscript{x}alab\textsubscript{a}a</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Harmony</strong></td>
<td>c. p\textsubscript{x}alap\textsubscript{a}a</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td><strong>Dissimilation</strong></td>
<td>d. p\textsubscript{x}alam\textsubscript{y}a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>
A factorial typology of ABC with \texttt{cvc-CC}

<table>
<thead>
<tr>
<th>Harmony</th>
<th>Short-Range \texttt{...CvC...}</th>
<th>Longer-Range \texttt{...Cv...vC...}</th>
<th>ABC: Possible with \texttt{cvc-CC}?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transvocalic</td>
<td><img src="#" alt="Green" /></td>
<td><img src="#" alt="Green" /></td>
<td>✓</td>
</tr>
<tr>
<td>Unbounded</td>
<td><img src="#" alt="Green" /></td>
<td><img src="#" alt="Green" /></td>
<td>✓</td>
</tr>
<tr>
<td>Beyond-transvocalic</td>
<td><img src="#" alt="Gray" /></td>
<td><img src="#" alt="Gray" /></td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dissimilation</th>
<th>Short-Range \texttt{...CvC...}</th>
<th>Longer-Range \texttt{...Cv...vC...}</th>
<th>ABC: Possible with \texttt{cvc-CC}?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transvocalic</td>
<td><img src="#" alt="Red" /></td>
<td><img src="#" alt="Gray" /></td>
<td>X</td>
</tr>
<tr>
<td>Unbounded</td>
<td><img src="#" alt="Red" /></td>
<td><img src="#" alt="Gray" /></td>
<td>✓</td>
</tr>
<tr>
<td>Beyond-transvocalic</td>
<td><img src="#" alt="Red" /></td>
<td><img src="#" alt="Gray" /></td>
<td>✓</td>
</tr>
</tbody>
</table>
## A comparison with TSL languages

<table>
<thead>
<tr>
<th></th>
<th>Short-Range ( \ldots \text{CvC}\ldots )</th>
<th>Longer-Range ( \ldots \text{CvC} \ldots \text{vC}\ldots )</th>
<th>ABC: Possible with ( \text{cvc-CC} )?</th>
<th>TSL(_2) Pattern?</th>
<th>Associated Learning Bias?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Harmony</strong></td>
<td>Transvocalic</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Unbounded</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Beyond-transvocalic</td>
<td>( X )</td>
<td>( X )</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td><strong>Dissimilation</strong></td>
<td>Transvocalic</td>
<td>( X )</td>
<td>✓</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unbounded</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beyond-transvocalic</td>
<td>✓</td>
<td>( X )</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>
## Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- Long-distance dissimilation in the subregular hierarchy
- A factorial typology of ABC constraints for dissimilation (and harmony)
- **Experimental results for studies of consonant dissimilation**
- Sketching out the problem and discussing possible solutions
More experiments with liquid dependencies

• A series of artificial phonology experiments being done in collaboration with Gunnar Ólafur Hansson
  • I will present a preliminary analysis of the results
• Analogous to the study of liquid harmony learning biases
• Extended along two dimensions
  1. Harmony vs. Dissimilation
  2. Liquids at one locality level vs. two locality levels
Liquid harmony (Restricted training)

- 3 training conditions
  - Liquids at only one locality level (no liquids for Control)
Liquid dissimilation (Restricted training)

- 3 training conditions
  - Liquids at only one locality I

![Graph showing proportions of dissimilation responses for different conditions and distances]

- Training Condition:
  - Control
  - Short-range Dissimilation
  - Medium-range Dissimilation

- Testing Distance:
  - Proportion of dissimilation responses
More experiments with liquid dependencies

- A series of artificial phonology experiments being done in collaboration with Gunnar Ólafur Hansson
  - I will present a preliminary analysis of the results
- Analogous to the study of liquid harmony learning biases
- Extended along two dimensions
  1. Harmony vs. Dissimilation
     - Both patterns attested for liquids
  2. Liquids at one locality level vs. two locality levels
     - Dependency holds at one distance, faithfulness at the other
       - Transvocalic harmony and dissimilation (attested)
       - Beyond-transvocalic harmony (unattested) and dissimilation (?)
     - How do subjects learn unbounded harmony in the face of counterevidence at CvC distance?
Liquid harmony (Counterevidence)

- 3 training conditions
  - Liquids at two locality levels (no liquids for Control)
Liquid dissimilation (Counterevidence)

- 3 training conditions
  - Liquids at two locality levels (no liquids for Control)

![Graph showing proportion of dissimilation responses for different training conditions and testing distances.]

**Training Condition**
- Control (no liquids)
- Short-Diss, Med-Faith
- Short-Faith, Med-Diss
### Outline and progress

<table>
<thead>
<tr>
<th>Evidence (Typology/Experiments)</th>
<th>Phonological theory (ABC)</th>
<th>Formal language theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A complete picture of harmony</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Putting it all together</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- Long-distance dissimilation in the subregular hierarchy
- A factorial typology of ABC constraints for dissimilation (and harmony)
- Experimental results for studies of consonant dissimilation
- Sketching out the problem and discussing possible solutions
Optimality Theory

A constraint (re)ranking algorithm that accounts for all training items

Formal Language Theory

An algorithm that maps training strings to a formal grammar

A factorial typology of **harmony and dissimilation** with ABC constraints

Tier-based Strictly Local languages

Attested languages

Hypothesis space
(Human-learnable languages)
• What is the actual hypothesis space of the human learner?
  • Continue assessing the typology of attested patterns
  • More experimental studies investigating human learning bias
Some possible solutions to discuss

- Modify the treatment of locality in ABC
  - No constraints that *penalize* correspondence outside of some context or domain (CC-\textsc{SyllAdj}, \textsc{Proximity}, \textsc{Cvc}-\textsc{CC})
  - Only constraints that *require* correspondence within that window (e.g., \textsc{Corr}[\textsc{G}]_{\textsc{Cvc}}; see Gunnar Ólafur Hansson’s talk today)
    - No consequences for harmony
    - No possibility of beyond CVC dissimilation (Sundanese? Bennett 2013)
    - Transvocalic dissimilation is no longer a problem
- Restrict the set of possible constraint rankings
- Have a theory of constraint learning
  - A learner only uses one of \textsc{Cvc}-\textsc{CC} or \textsc{Corr}[\textsc{G}]_{\textsc{Cvc}} depending on the target pattern
- Further investigation of formal languages
  - Especially an understanding of the relationship between phonological mappings and phonotactic restrictions
Acknowledgements

- Gunnar Ólafur Hansson
- Carla Hudson Kam – UBC Language and Learning Lab
- Douglas Pulleyblank, Masaki Noguchi, Raphael Girard
- Alexis Black, James Crippen, Ella Fund-Reznicek, Michael McAuliffe

- UBC Arts Graduate Research Award (Kevin McMullin)

- Various audiences providing feedback: NELS44 (Storrs, CT), members of UBC Ling530 graduate seminars (Perception and Production, Formal Models of Learning, Tone)
References


References


References


