a place of mind

UBC

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

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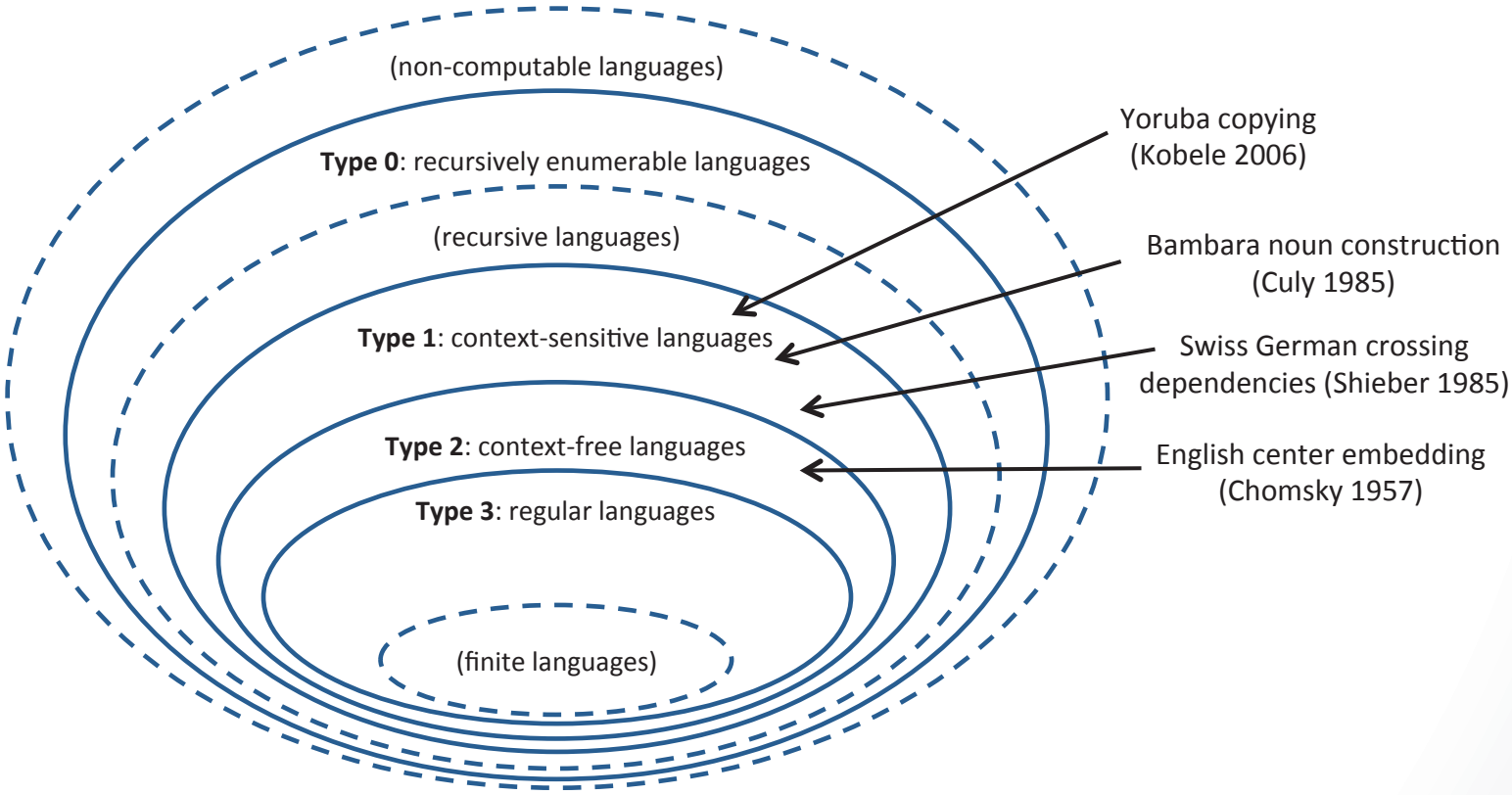
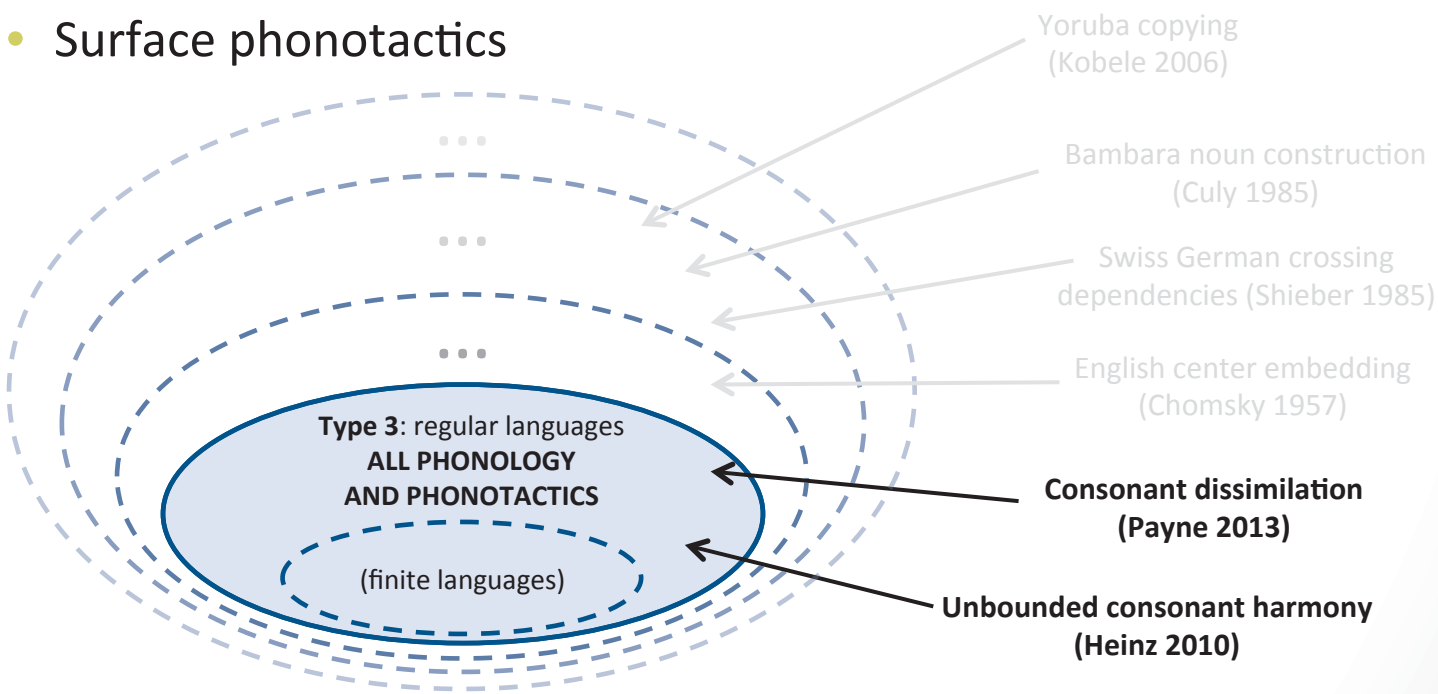
Formal/computational language theory

- 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



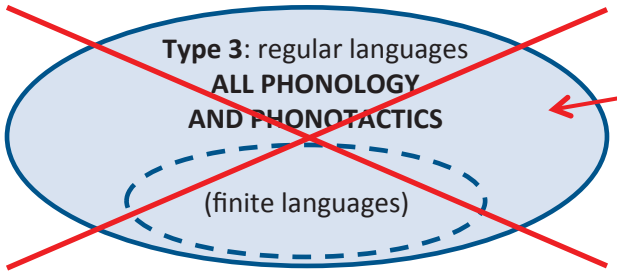
Formal/computational language theory

- 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



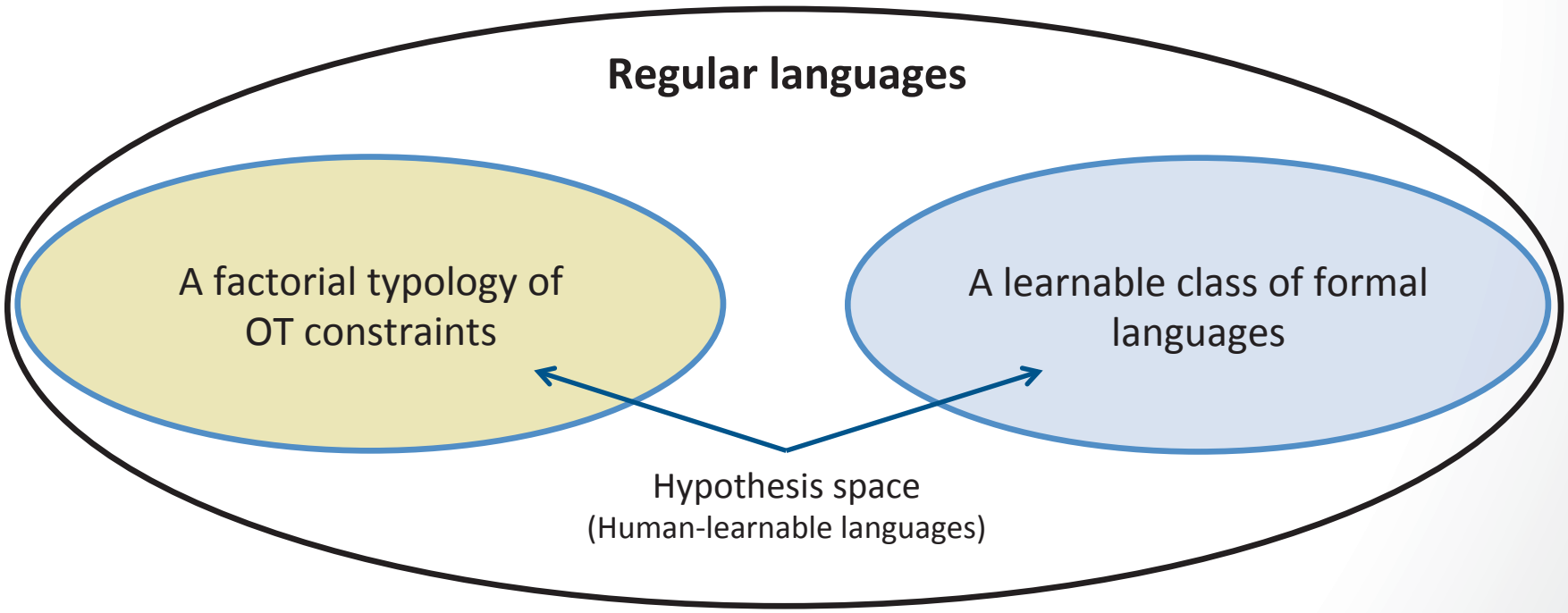
This cannot be the learner's hypothesis space

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
  - …<u>from POSITIVE data</u>
    - 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



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)

A factorial typology of OT constraints ≠ A learnable class of formal languages

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

	Evidence (Typology/ Experiments)	Phonological theory (ABC)	Formal language theory
Consonant harmony	1.		
		2.	
			3.
	4. A complete picture of harmony		
Consonant dissimilation			5.
		6.	
	7.		
	8. Putting it all together		

- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
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- Everything looks good so far
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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’
    -tsú**m**-i**n**i ‘sew-PFV’
    -**m**íːtuk-i**n**i ‘sulk-PFV’
- TRANSVOCALIC – holds across at most one vowel (CvC sequences)
  - Example: Lamba nasal consonant harmony (Odden 1994)

    -pat-ile ‘scold-PFV’
    -uː**m**-i**n**e ‘dry-PFV’
    -**m**as-i**l**e ‘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 cvSv-Sv harmony to Svcv-Sv
  - Learners **do** generalize cvSvcv-Sv, both to cvcvSv-Sv and Svcvcv-Sv
- McMullin (2013)
  - Replicates result with suffix-to-root sibilant harmony
- Sibilant harmony in the absence of other information
  - …SvS… learned as a **transvocalic** dependency
  - …SvcvS… 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*}…
  - …{*korupe…kolupe-li…korupe-ru*}…
  - …{*torite…torite-ru…tolite-li*}…

Liquid harmony experiment: Testing

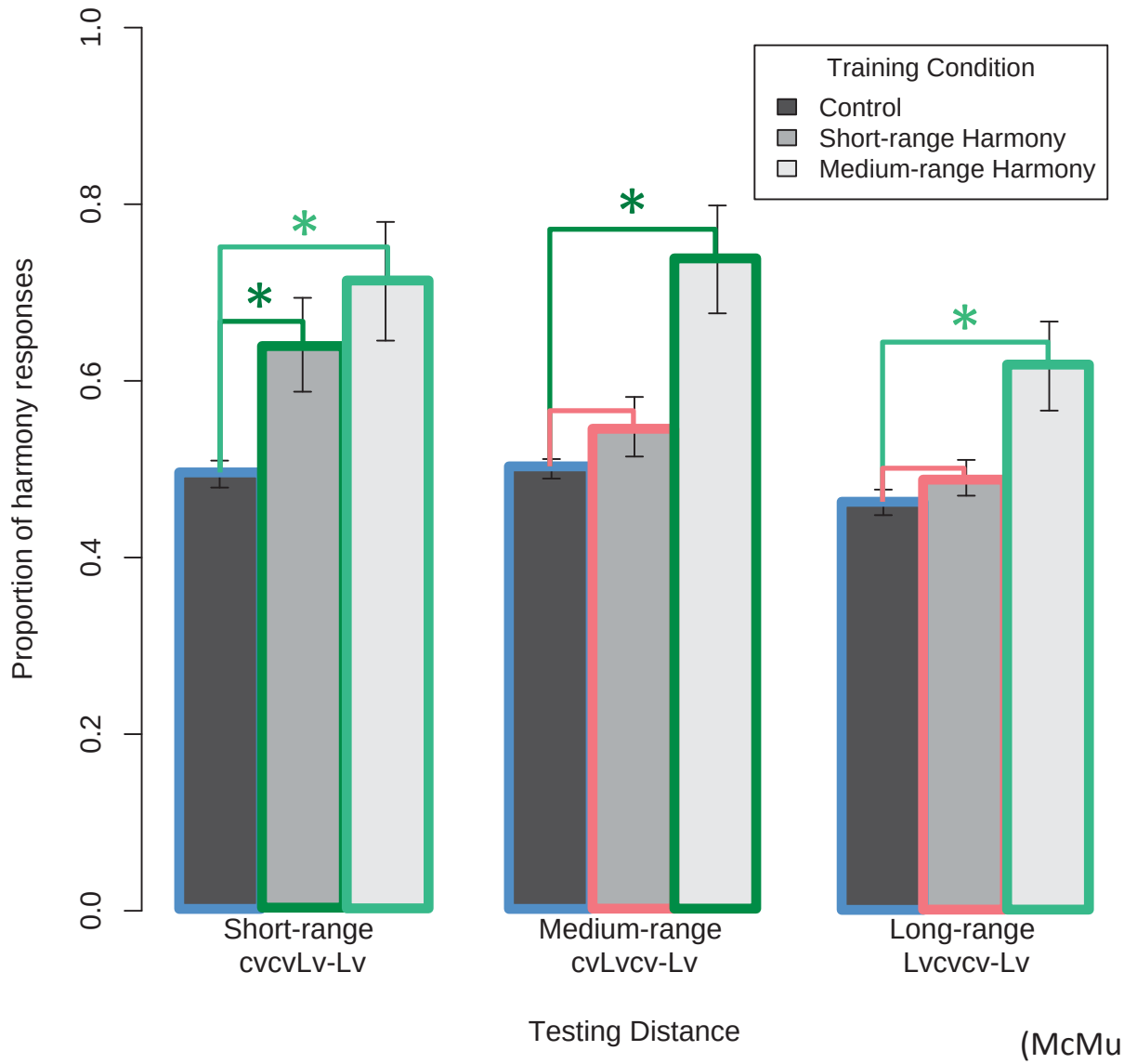
(McMullin and Hansson 2013)

- 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

	…Cv-Cv	…Cvcv-Cv	Cvcvcv-Cv
transvocalic	+	–	–
unbounded	+	+	+
unattested	–	+	–
unattested	+	+	–
unattested	–	+	+

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

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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**

(…CvC…)	/lapaba/		IDENT [son]-IO	CORR [-son]	IDENT [voi]-CC	IDENT [voi]-IO
Faithful	a. lap_xab_ya			*!		
Faithful	b. lap_xab_xa				*!	
Harmony	☞c. lap_xap_xa					*
Dissimilation	d. lap_xam_ya		*!			

(…CvcvC…)	/palaba/		IDENT [son]-IO	CORR [-son]	IDENT [voi]-CC	IDENT [voi]-IO
Faithful	a. p_xalab_ya			*!		
Faithful	b. p_xalab_xa				*!	
Harmony	☞c. p_xalap_xa					*
Dissimilation	d. p_xalam_ya		*!			

Transvocalic harmony

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

(…CvC…)	/lapaba/	**cvc-CC**	IDENT [son]-IO	CORR [-son]	IDENT [voi]-CC	IDENT [voi]-IO
Faithful	a. lap_xab_ya			*!		
Faithful	b. lap_xab_xa				*!	
Harmony	☞c. lap_xap_xa					*
Dissimilation	d. lap_xam_ya		*!			

(…CvcvC…)	/palaba/	**cvc-CC**	IDENT [son]-IO	CORR [-son]	IDENT [voi]-CC	IDENT [voi]-IO
Faithful	☞a. p_xalab_ya			*		
Faithful	b. p_xalab_xa	*!			*	
Harmony	c. p_xalap_xa	*!				*
Dissimilation	d. p_xalam_ya		*!			

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The OT account of…

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

- Learnability
  - Innate constraints are learning biases
    - cvc-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

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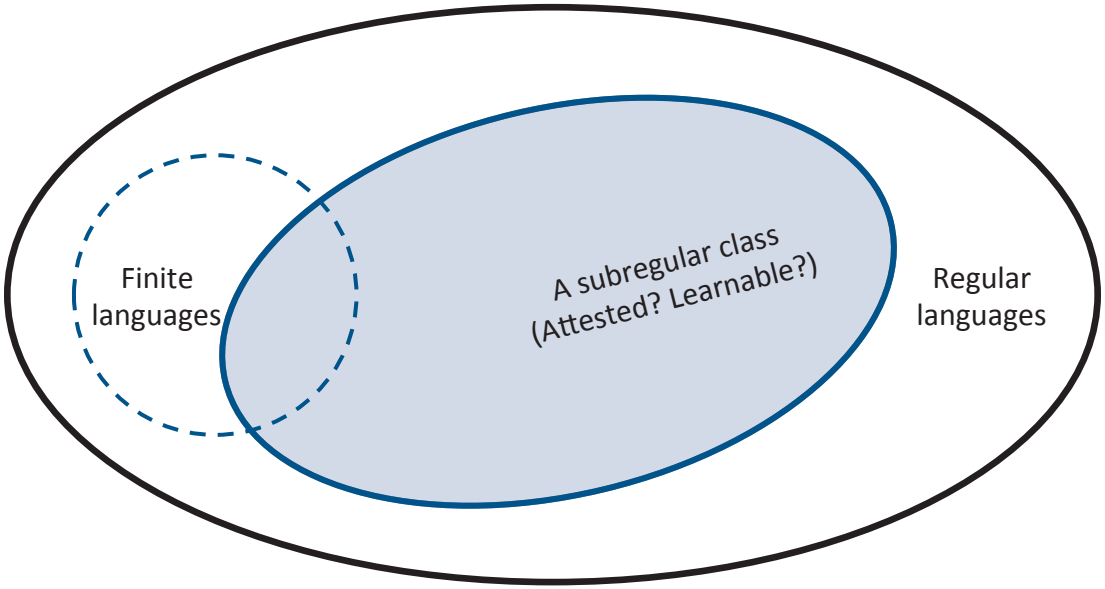
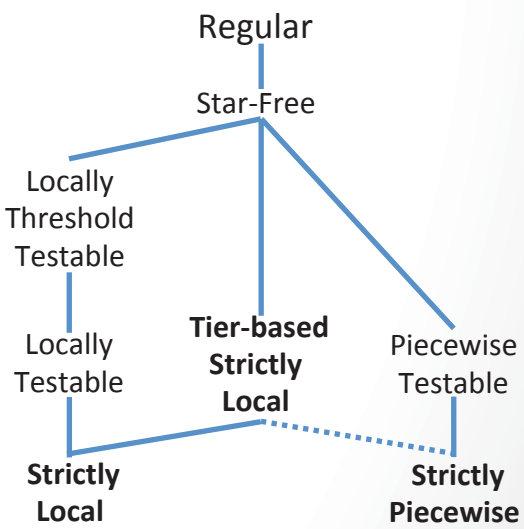
The subregular hierarchy

(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**
    - *siʃ, *ʃas (but sV…Vʃ 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. {*lVɹ, *ɹVl} 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 (SP_k)

(Heinz 2010)

- Unbounded co-occurrence restrictions
  - SP_2 patterns prohibit *x…y* subsequences
  - **Unbounded harmony can be described as SP_2** (*s…ʃ, *ʃ…s)

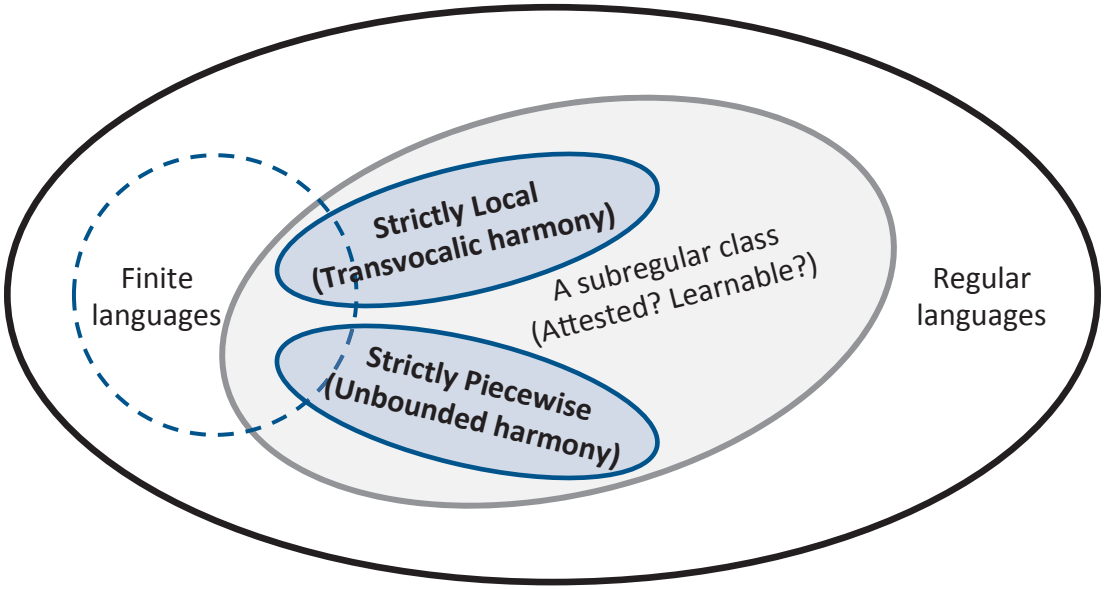
- SP languages are learnable (Heinz 2010)
  - With an algorithm that records all encountered *k*-subsequences
    - 'abcd' → {a…b, a…c, a…d, b…c, b…d, c…d}
  - The grammar is a set of permitted (prohibited) subsequences
    - {*l…ɹ, *ɹ…l} for unbounded liquid harmony

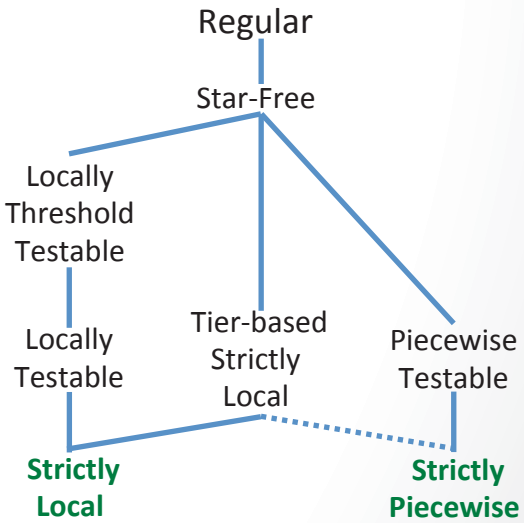
A modular account of learning bias

- 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 Idsardi 2011; Lai 2012)

  - Learners use a SL_3 learning algorithm for transvocalic harmony
    - This happens first for experimental learners (no generalization)
  - Learners use a SP_2 learning algorithm for unbounded harmony





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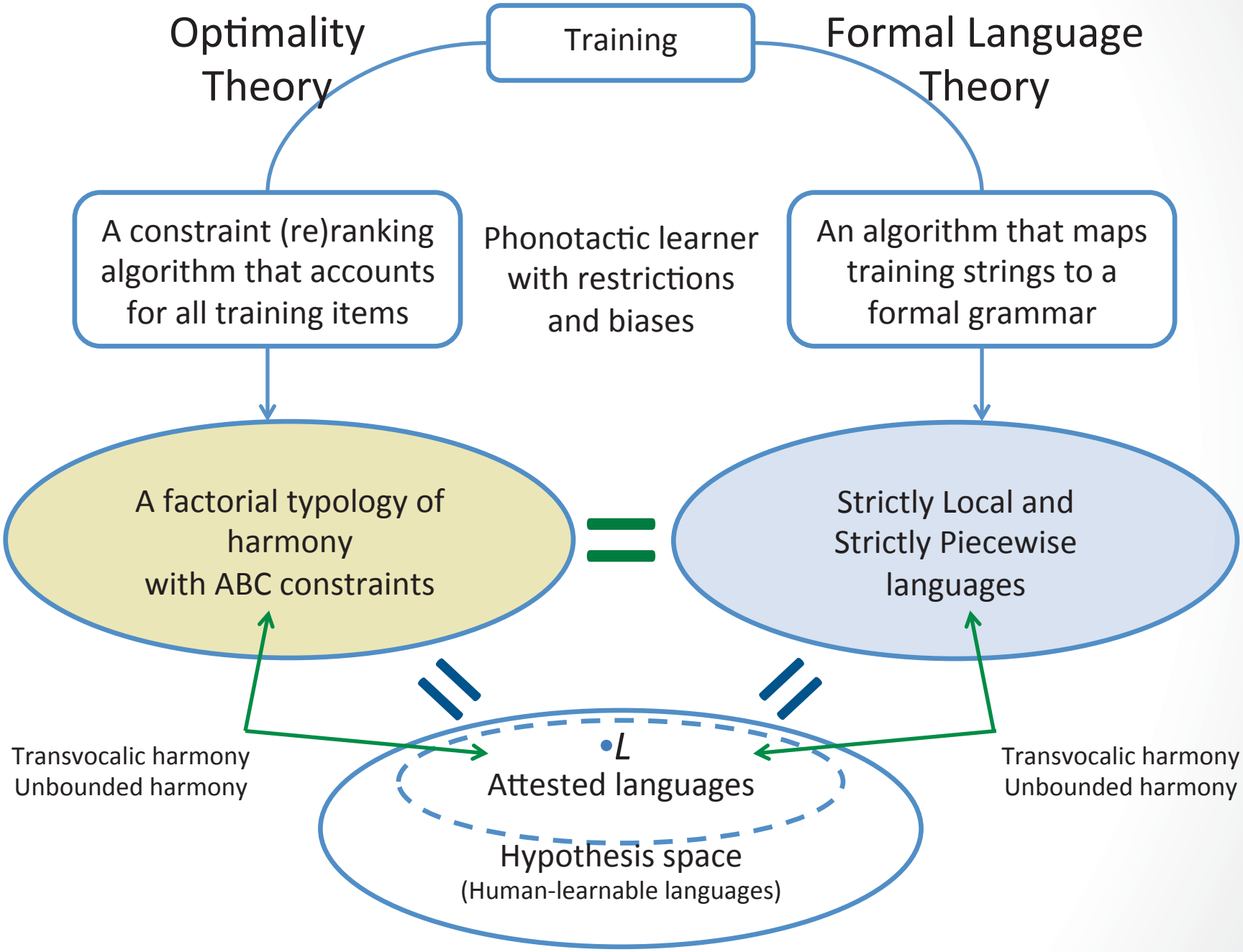
Optimality Theory
Training
Formal Language Theory
A constraint (re)ranking algorithm that accounts for all training items
Phonotactic learner with restrictions and biases
An algorithm that maps training strings to a formal grammar
A factorial typology of harmony with ABC constraints
=
Strictly Local and Strictly Piecewise languages
Transvocalic harmony
Unbounded harmony
•L
Attested languages
Hypothesis space
(Human-learnable languages)
Transvocalic harmony
Unbounded harmony

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Evidence against a SL+SP hypothesis space

- Dissimilation with blocking is attested
  - Example: Latin liquid dissimilation (Jensen 1974; Odden 1994)
    - /lun-alis/ → [lun-aris] *l…l is prohibited
    - /flor-alis/ → [flor-alis] *[flor-aris] 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-alis/ → [lun-aris] is now: /ll/ → [lr]
  - /flor-alis/ → [flor-alis] is now: /lrl/ → [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 'piɹeʃaʃolu':
  - Vowel tier – ieaou — p**i**ɹ**e**ʃ**a**ʃ**o**l**u**
  - Consonant tier – pɹʃʃl — **p**i**ɹ**e**ʃ**a**ʃ**o**l**u**
  - Sibilant tier – ʃʃ — piɹe**ʃ**a**ʃ**olu
  - Liquid tier – ɹl — piɹeʃaʃo**l**u
  - {ʃ,p,i,u} tier – piʃʃu — **p**i**ʃ**e**ʃ**a**ʃ**o**l**u**

- **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
  - *tasaʃ {ts, *sʃ}
  - sataʃ {st, tʃ}
- Unbounded dependencies are TSL_2 on the sibilant tier
  - *tasaʃ {*sʃ}
  - *sataʃ {*sʃ}
- 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
  - *sapaʃ {*sʃ}
  - sataʃ {st, tʃ}

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 *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 *phonotactic* patterns
    - Is there an analogous way to discuss phonological mappings?

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Dissimilation: Unbounded

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

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Faithful	b. lap_xab_xa			*!		
Harmony	c. lap_xap_xa	*!				
Dissimilation	☞d. lap_xam_ya					*

(…CvcvC…)	/palaba/	IDENT [voi]-IO	CORR [-son]	IDENT [voi]-CC	CVC-CC	IDENT [son]-IO
Faithful	a. p_xalab_ya		*!			
Faithful	b. p_xalab_xa			*!	*(!)	
Harmony	c. p_xalap_xa	*!			*(!)	
Dissimilation	☞d. p_xalam_ya					*

Dissimilation: Unbounded

- Note: **Identical consonants** will not dissimilate at CvC locality
  - Nothing forces them out of correspondence

(…CvC…)	/lababa/	IDENT [voi]-IO	CORR [-son]	IDENT [voi]-CC	CVC-CC	IDENT [son]-IO
Faithful	a. lab_xab_ya		*!			
Faithful	b. lab_xab_xa					
Harmony	☞c. lab_xab_xa					
Dissimilation	d. lab_xam_ya					*

(…CvcvC…)	/balaba/	IDENT [voi]-IO	CORR [-son]	IDENT [voi]-CC	CVC-CC	IDENT [son]-IO
Faithful	a. b_xalab_ya		*!			
Faithful	b. b_xalab_xa				*!	
Harmony	c. b_xalab_xa				*!	
Dissimilation	☞d. b_xalam_ya					*

Dissimilation: Transvocalic

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

(…CvC…)	/lapaba/	IDENT [voi]-IO	CORR [-son]	IDENT [voi]-CC	CVC-CC	IDENT [son]-IO
Faithful	a. lap_xab_ya		*!			
Faithful	b. lap_xab_xa			*!		
Harmony	c. lap_xap_xa	*!				
Dissimilation	☞d. lap_xam_ya					*

(…CvcvC…)	/palaba/	IDENT [voi]-IO	CORR [-son]	IDENT [voi]-CC	CVC-CC	IDENT [son]-IO
Faithful	a. p_xalab_ya		*!			
Faithful	b. p_xalab_xa			*!	*(!)	
Harmony	c. p_xalap_xa	*!			*(!)	
Dissimilation	☞d. p_xalam_ya					*

Dissimilation: Beyond-transvocalic

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

(…CvC…)	/lapaba/	CVC-CC	CORR [-son]	IDENT [son]-IO	IDENT [voi]-IO	IDENT [voi]-CC
Faithful	a. lap_xab_ya		*!			
Faithful	☞b. lap_xab_xa					*
Harmony	☞c. lap_xap_xa				*	
Dissimilation	d. lap_xam_ya			*!		

(…CvcvC…)	/palaba/	CVC-CC	CORR [-son]	IDENT [son]-IO	IDENT [voi]-IO	IDENT [voi]-CC
Faithful	a. p_xalab_ya		*!			
Faithful	b. p_xalab_xa	*!				*
Harmony	c. p_xalap_xa	*!			*	
Dissimilation	☞d. p_xalam_ya			*		

A factorial typology of ABC with cvc-CC

	Short-Range …CvC…	Longer-Range …Cv…vC…	ABC: Possible with cvc-CC?
Harmony	Transvocalic		✓
Harmony	Unbounded		✓
Harmony	Beyond-transvocalic		X
Dissimilation	Transvocalic		X
Dissimilation	Unbounded		✓
Dissimilation	Beyond-transvocalic		✓

A comparison with TSL languages

	Short-Range …CvC…	Longer-Range …Cv…vC…	ABC: Possible with cvc-CC?	TSL_2 Pattern?	Associated Learning Bias?
Harmony	Transvocalic		✓	✓	✓
Harmony	Unbounded		✓	✓	✓
Harmony	Beyond-transvocalic		X	X	?
Dissimilation	Transvocalic		X	✓	?
Dissimilation	Unbounded		✓	✓	?
Dissimilation	Beyond-transvocalic		✓	X	?

Outline and progress

	Evidence (Typology/ Experiments)	Phonological theory (ABC)	Formal language theory
Consonant harmony	1.		
		2.	
			3.
	4. A complete picture of harmony		
Consonant dissimilation			5.
		6.	
	7.		
	8. Putting it all together		

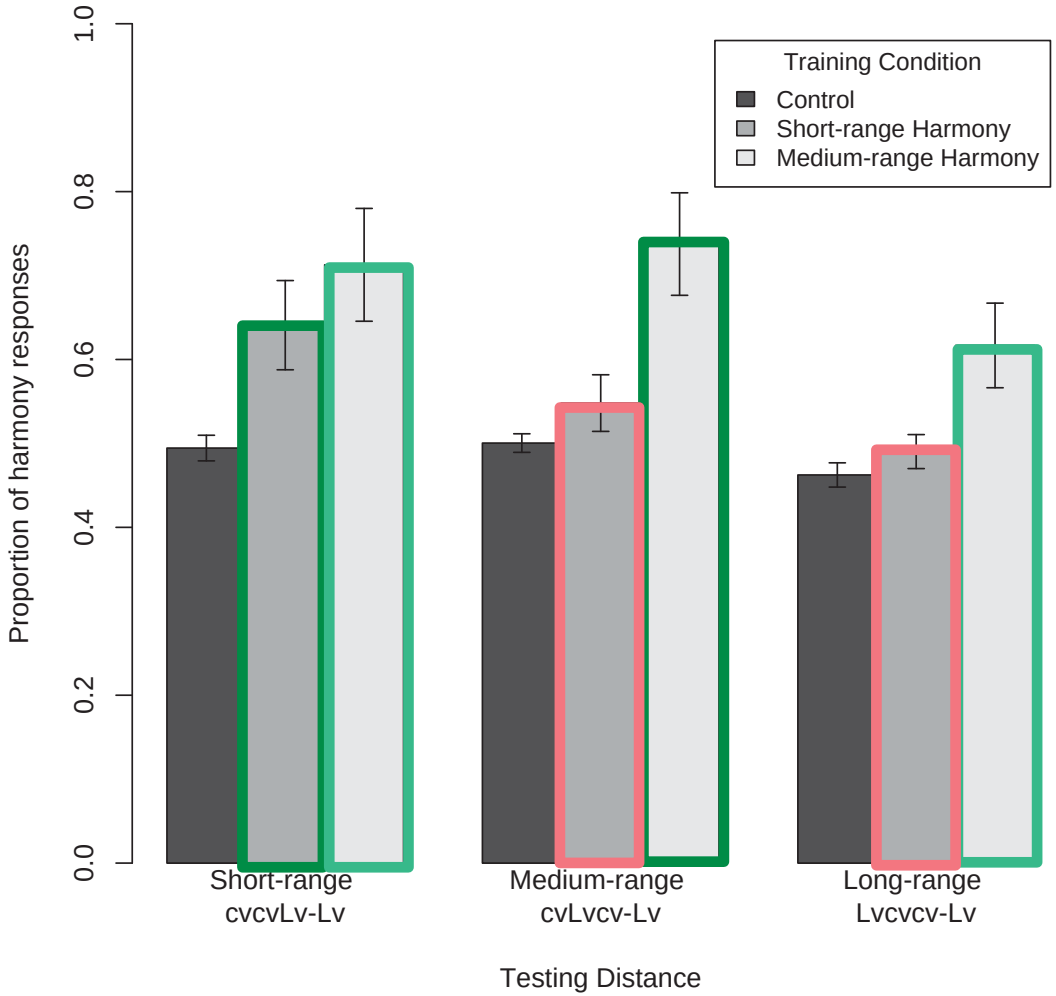
- The typology of consonant harmony and experimental learning bias
- Transvocalic vs. unbounded harmony in Agreement by Correspondence
- Subregular accounts of consonant harmony learnability
- Everything looks good so far
- Long-distance dissimilation in the subregular hierarchy
- A factorial typology 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

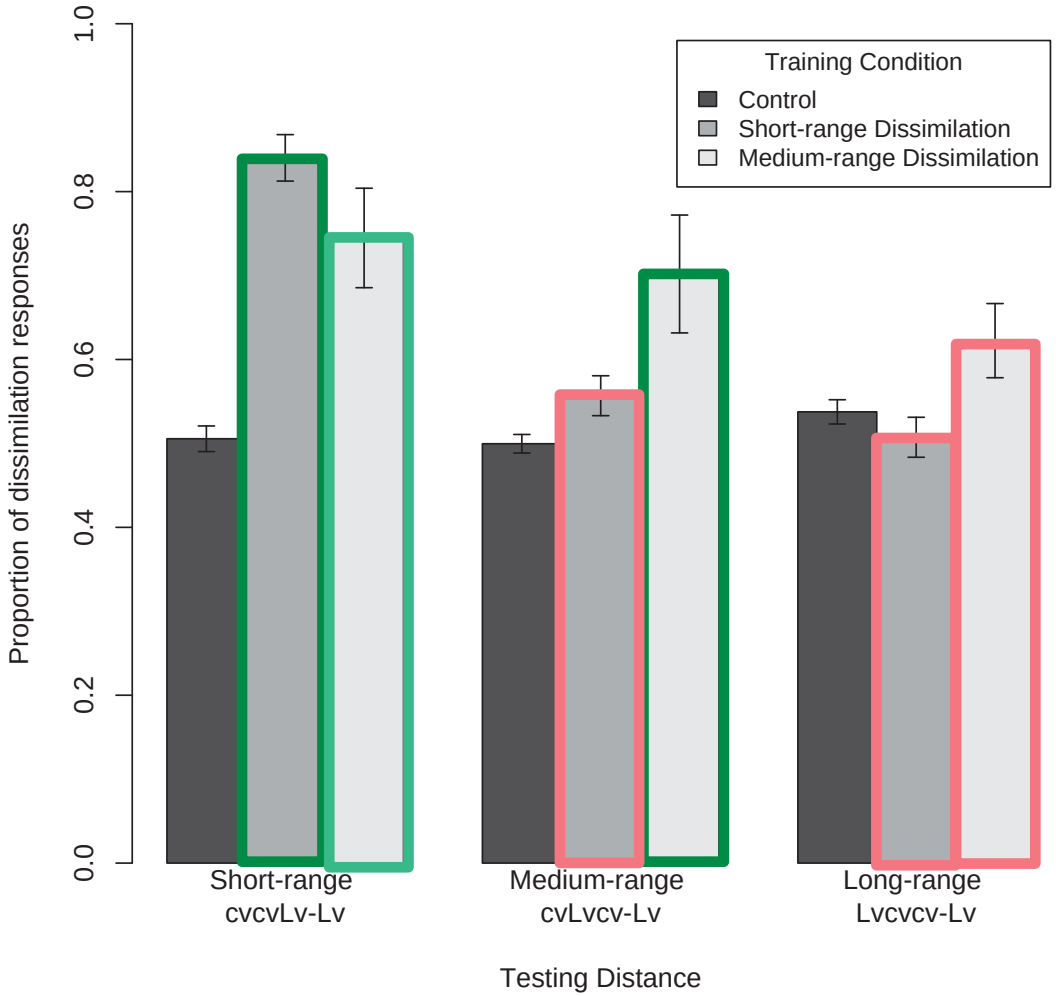
Liquid harmony (Restricted training)

- 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 l

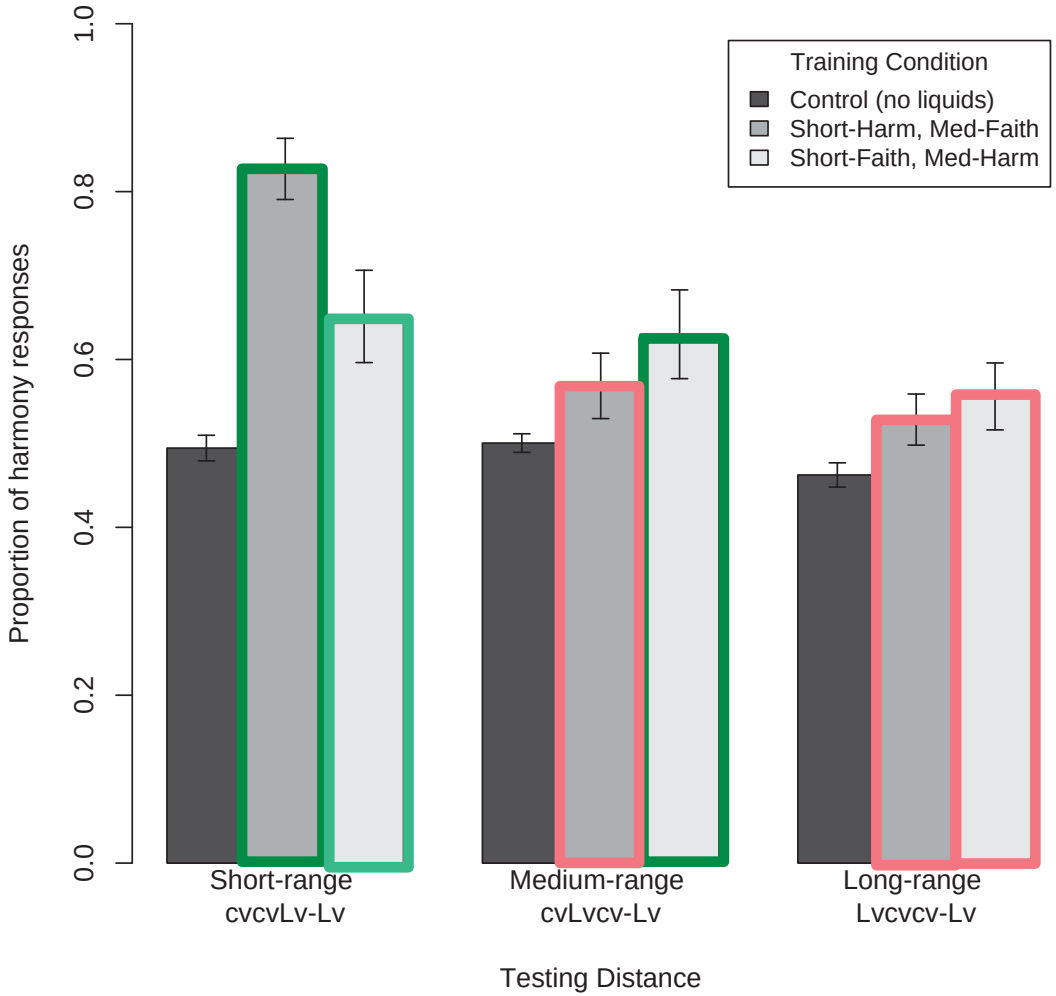


More experiments with liquid dependencies

- 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?

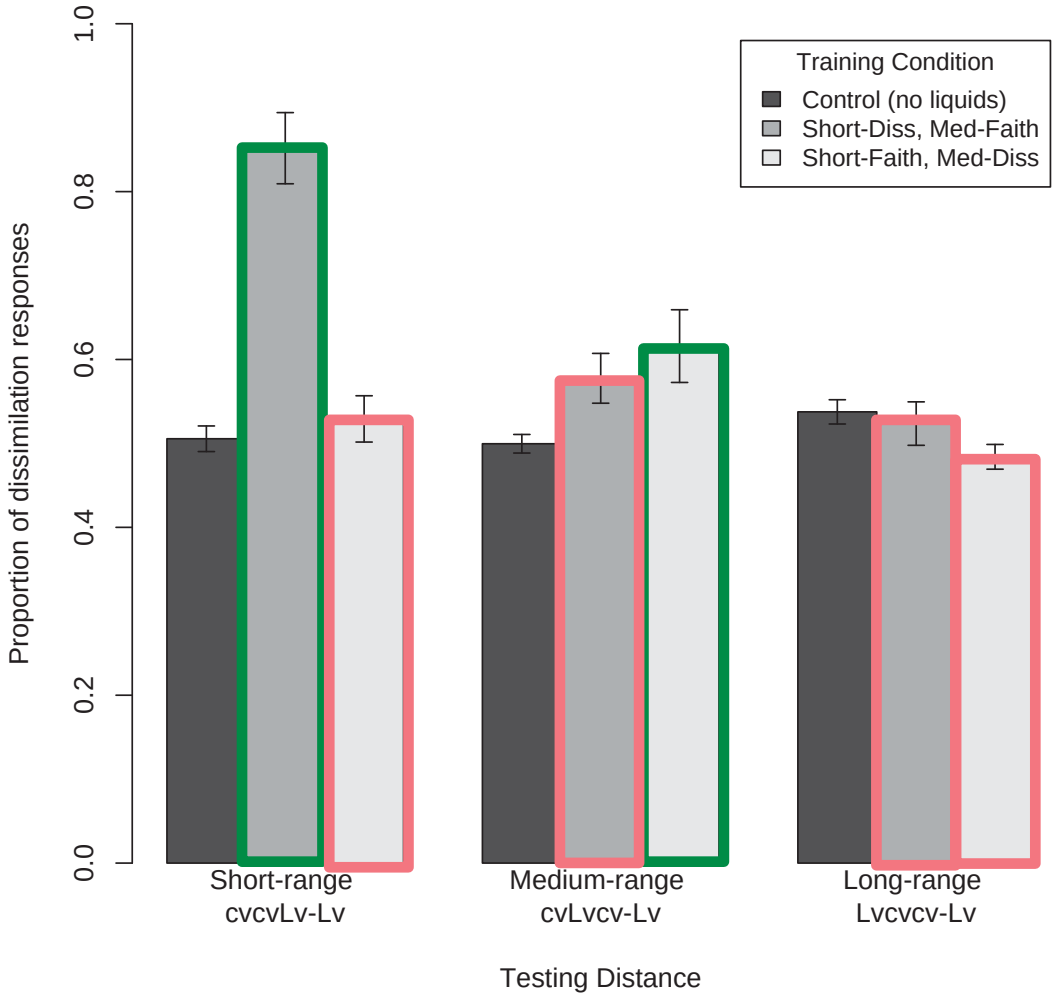
Liquid harmony (Counterevidence)

- 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)



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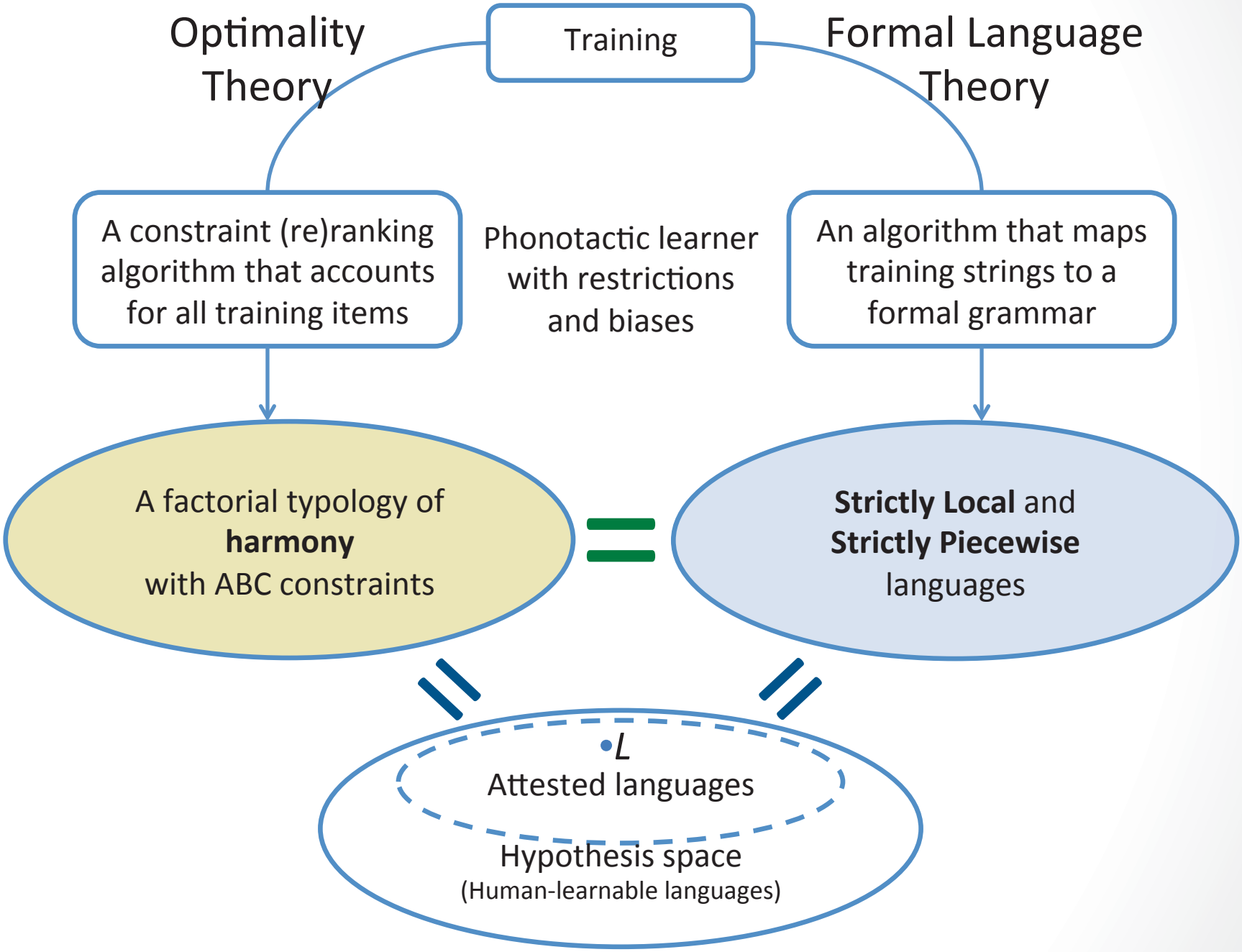
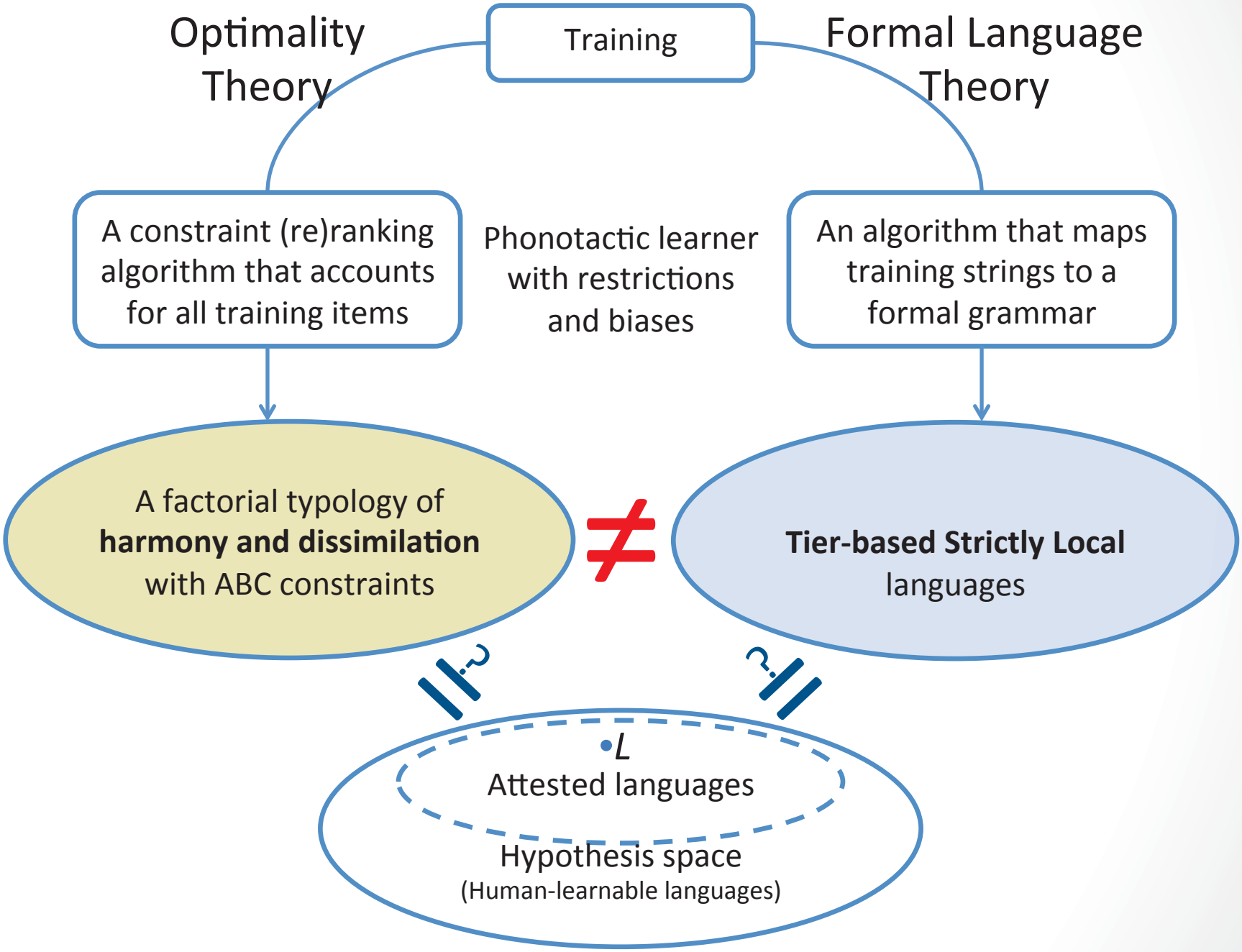

Optimality Theory
Training
Formal Language Theory
A constraint (re)ranking algorithm that accounts for all training items
Phonotactic learner with restrictions and biases
An algorithm that maps training strings to a formal grammar
A factorial typology of **harmony** with ABC constraints
Strictly Local and **Strictly Piecewise** languages
•L
Attested languages
Hypothesis space
(Human-learnable languages)


Training
Optimality Theory
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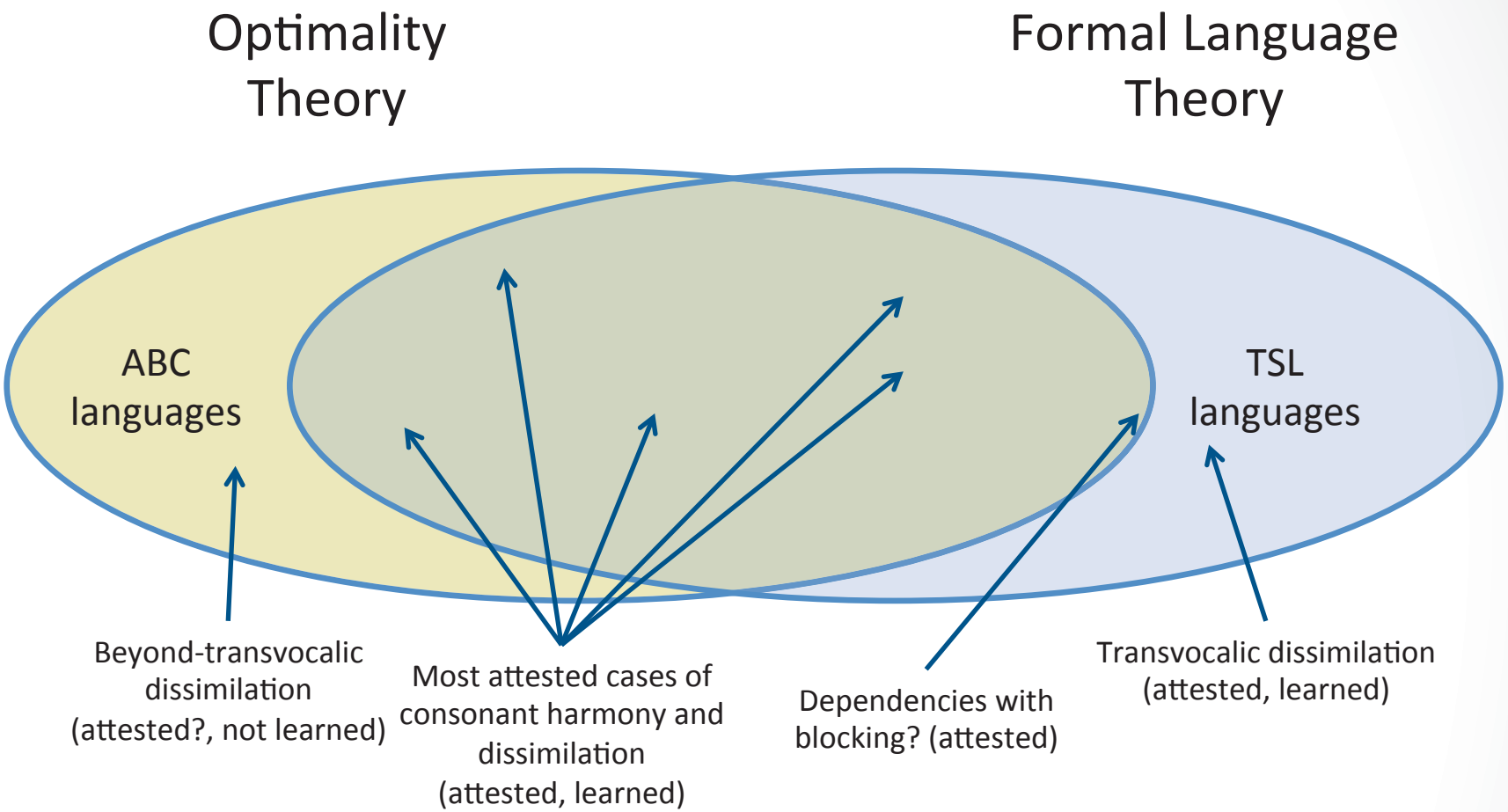
A factorial typology of **harmony and dissimilation** with ABC constraints
≠
Tier-based Strictly Local languages
L
Attested languages
Hypothesis space
(Human-learnable languages)



- 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-SYLLADJ, PROXIMITY, $\underline{C}V\underline{C}$-CC)
  - Only constraints that *require* correspondence within that window (e.g., CORR[G]$_{\underline{C}V\underline{C}}$; 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 $\underline{C}V\underline{C}$-CC or CORR[G]$_{\underline{C}V\underline{C}}$ depending on the target pattern
- Further investigation of formal languages
  - Especially an understanding of the relationship between phonological mappings and phonotactic restrictions

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