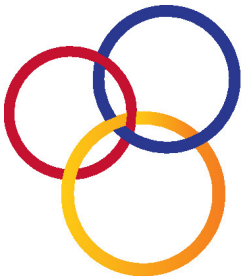
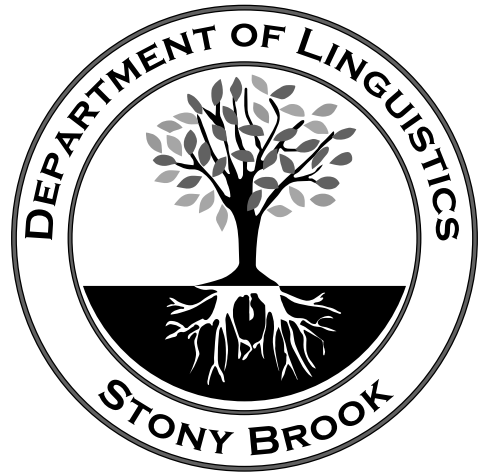
The Computational Structure of Phonological and Phonetic Knowledge

Scott Nelson
Stony Brook University

University of Utah
January 30, 2024



iACS
INSTITUTE FOR ADVANCED COMPUTATIONAL SCIENCE



Is Phonological Knowledge Categorical or Gradient?

- Phonological Knowledge:
  - Representations
  - Rules/Constraints

- What's the nature of this knowledge?
  - Some feel that it is Categorical.
  - Others feel that is is Gradient.

Categorical: Jakobson et al. (1951), Chomsky and Halle (1968), McCarthy (2003), Bermúdez-Otero (2007), Reiss and Volenec (2020), Du and Durvasula (2024); **Gradient:** Coleman and Pierrehumbert (1997), Bybee (2001), Flemming (2001), Albright and Hayes (2006), Coetzee and Pater (2008), Ernestus (2011), Smolensky and Goldrick (2016), Lionnet (2017); among *many others* on both sides.

Empirical Phenomena Central to the Debate

1. Incomplete Neutralization
   - German final devoicing
   - Cantonese contracted syllables
   - Lebanese Arabic epenthesis
2. Variation in Homophone Duration
   - English homophone pairs

Port and O'Dell (1985), Port and Crawford (1989), Yu (2007), Gouskova and Hall (2009), Hall (2013), Gahl (2008)

Incomplete Neutralization

- Phonological Neutralization happens when a contrast is eliminated due to a phonological process.

- German final devoicing is a classic example.

/bad + en/	→	[baden]	'to bathe'
/bad/	→	[bat]	'bath'
/bat + en/	→	[baten]	'asked'
/bat/	→	[bat]	'ask'

Dinnsen and Garcia-Zamor (1971)

Incomplete Neutralization

- Laboratory experiments on final devoicing have shown that a phonologically neutralized segment has some phonetic properties similar to its underlying form.

- This is referred to as incomplete (phonetic) neutralization.
- Note: this is also not exclusive to final devoicing!

German: Port et al. (1981); Fourakis and Iverson (1984); Port and O'Dell (1985); Port and Crawford (1989); **Polish:** Slowiaczek and Dinnsen (1985); Jassem and Richter (1989); **Russian:** Dmitrieva et al. (2010); Shrager (2012); Kharlamov (2014); **Dutch:** Warner et al. (2004, 2006); **Catalan:** Dinnsen and Charles-Luce (1984); **Afrikaans:** Van Rooy et al. (2003)

A deathblow to formalism?

"...[incomplete neutralization] demonstrate[s] that the phonological structures employed by human speakers cannot provide the digital foundation for a formal system of language that is required by generative phonology as well as by all formal theories of language."

Port and Leary (2005) - *Against Formal Phonology*

Variation in Homophone Duration

- Homophones are not usually phonetically identical.
- Speech category can play a role ("road" vs. "rode").
- But frequency also plays a large role.
  - Arab grammarians of the Middle Ages noted that more frequent words become "weaker".
  - Words of the same grammatical class vary in duration based on frequency.

Walsh and Parker (1983); Losiewicz (1995); Fosler-Lussier and Morgan (1998); Bybee (2001); Jurafsky et al. (2001); Bell et al. (2009); Leslau (1969); Gahl (2008)

Another issue for discrete phonology?

"One set of implications of these results relates to the nature of phonological forms. The models of language production mentioned so far assume that phonological representations are composed of an alphabet of discrete segments...As we saw earlier, such a move is problematic for the current data..."

Gahl (2008) - *Time and thyme are not homophones*

Summary of Phenomena Central to the Debate

Variation in Homophone Duration

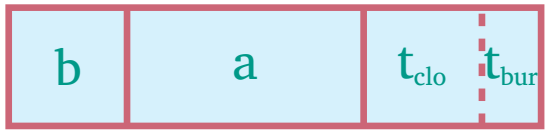
duration = x ms.

duration < x ms.

Within the same category of speech more frequent homophones are shorter in duration

Incomplete Neutralization

/t/ → [t]
closure duration = y ms
burst duration = z ms



/d/ → [t]
closure duration = y ms
burst duration < z ms

Phonologically neutralized segments show systematic similarities to their underlying form along certain cues

Focus of Today's Talk

The puzzle and how to solve it

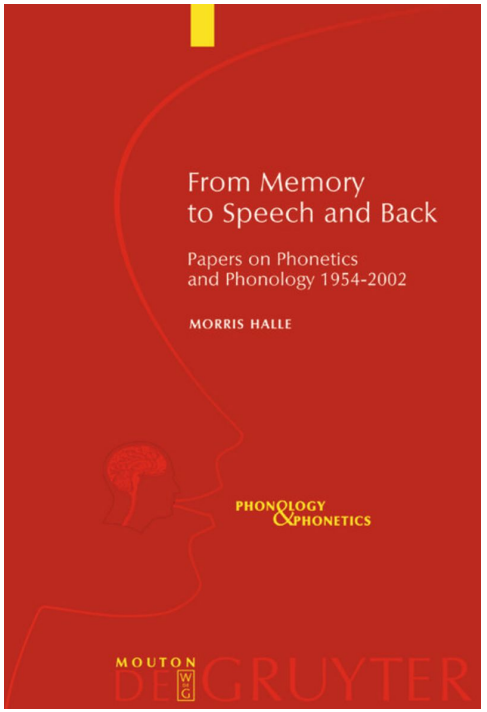
- Is it possible to maintain categorical phonological knowledge while still explaining systematic continuous phonetic phenomena?
- Yes. Their conclusions are only valid presuming a particular view of the structure of the phonetics-phonology interface: the modular feed-forward model.
- I provide an alternative structure of the phonetics-phonology interface that shows that categorical phonological knowledge can be maintained while still explaining systematic continuous phonetic phenomena.

Outline

Phonological and Phonetic Knowledge

Phonological and Phonetic Knowledge

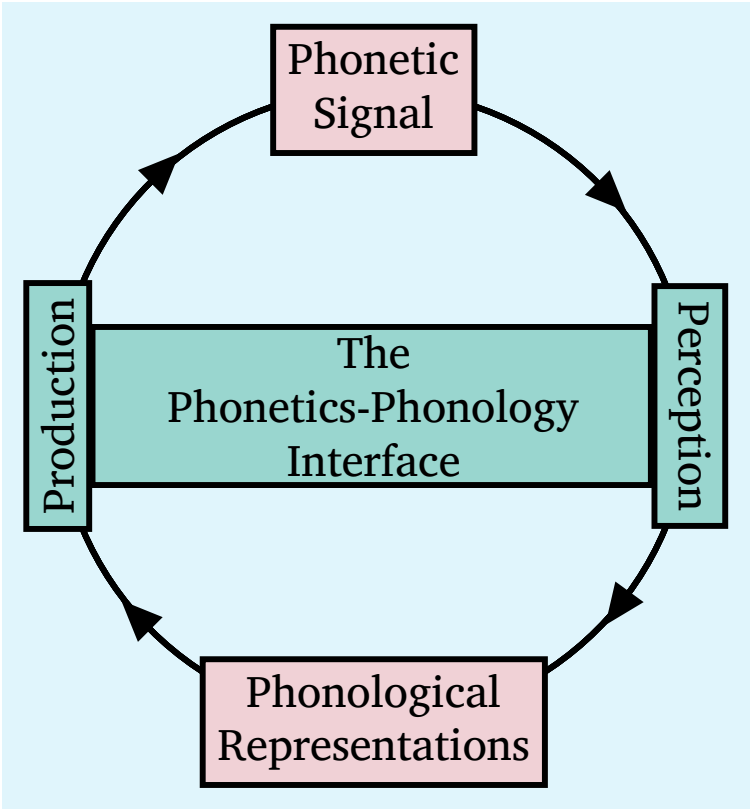
"...the overt aspects of language – the articulatory actions and the acoustic signal they produce – cannot be properly understood without reference to the covert aspect of language"



Halle (2003)

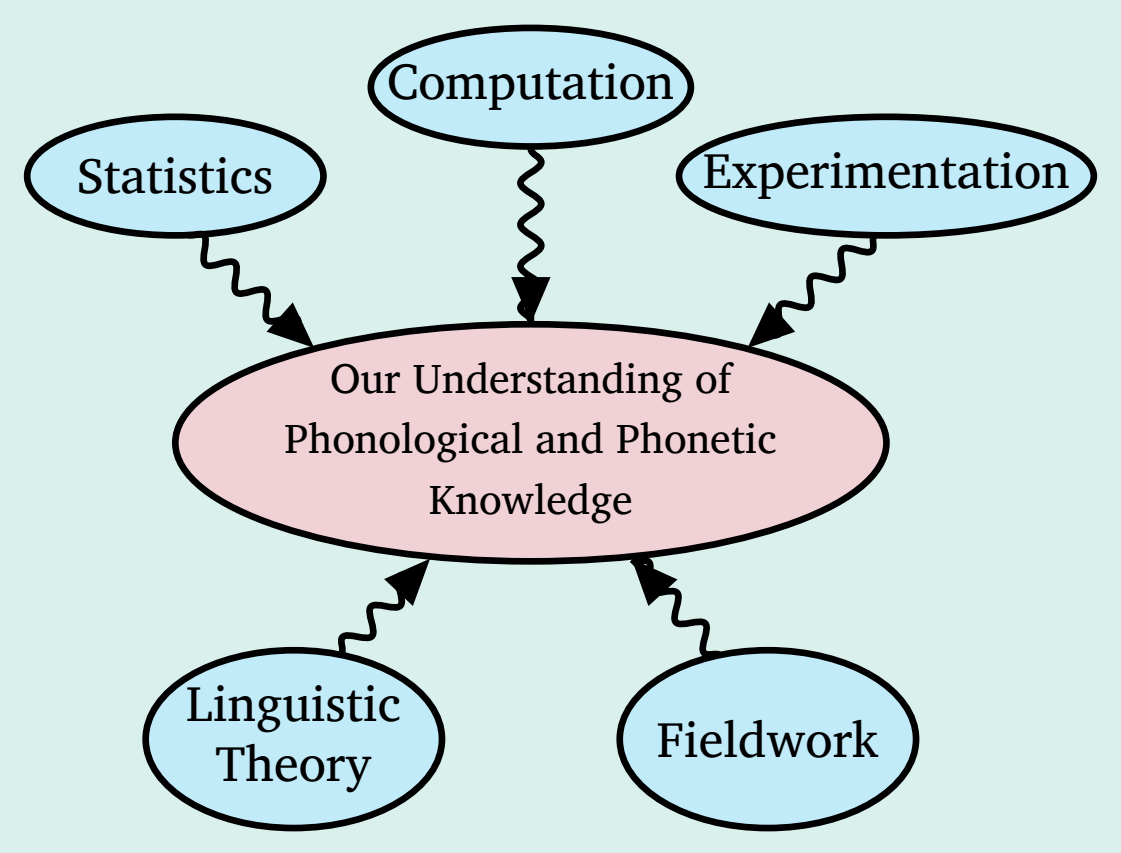
Phonological and Phonetic Knowledge

- The Phonetics-Phonology Interface is the translation mechanism between...
  - "the categories of the speaker's message to the utterance's articulatory continuum"
  - "the auditory continuum to the categories of the listener's recognition of the message's phonological content"



Kingston (2019)

A Multi-Faceted Approach

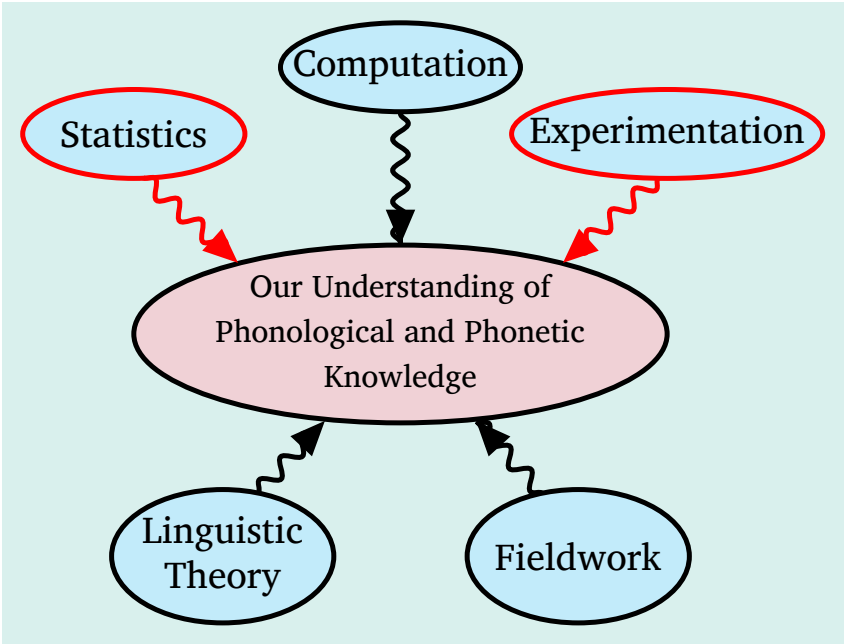


Durvasula and Nelson (2018), Nelson and Durvasula (2021), Taherkhani et al. (in prep), Taherkhani and Nelson (accepted), Nelson (to appear), Nelson (2022), Nelson (in prep), Nelson and Heinz (2022), Nelson and Heinz (submitted)

Speech Perception as a Window into Phonological Representation

Durvasula, K. and Nelson, S. (2018). Lexical re-tuning targets features. *Proceedings of the 2017 Annual Meeting on Phonology*.

Nelson, S. and Durvasula, K. (2021). Lexically-guided perceptual learning does generalize to new phonetic contexts. *Journal of Phonetics*.

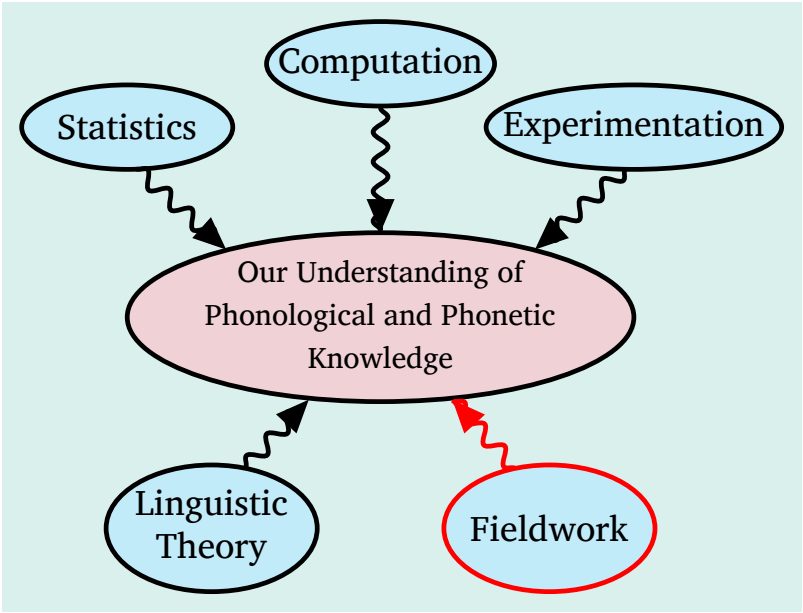


- We found that context-independent sub-segmental representations were implicated during the perception process, thus providing insight into representational knowledge.

Fieldwork as a Source of New Phenomena

Taherkhani, N. and Nelson, S. (accepted). Southern Tati: Takestani Dialect. *Journal of the International Phonetic Association*.

Taherkhani, N., Nelson, S., and Heinz, J. (in prep). A Contrastive Hierarchy for Vowels in Southern Tati: Takestani Dialect.



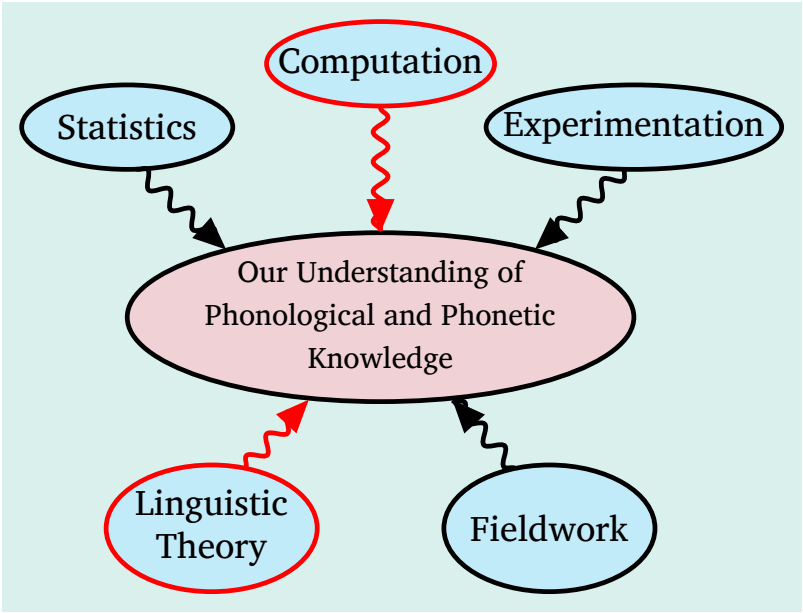
- We documented a typologically rare vowel inventory and showed its implications for the phonology of the language, thus expanding our understanding of what types of phonological and phonetic knowledge are possible.

Formalizing Theoretical Proposals

Nelson, S. (2022). A model theoretic perspective on phonological feature systems. *Proceedings of the Society for Computation in Linguistics*.

Nelson, S. (to appear). Process interaction and complexity. *Doing Computational Phonology*.

Nelson, S. (in prep). Inferring linear order from non-linear gestural representations.

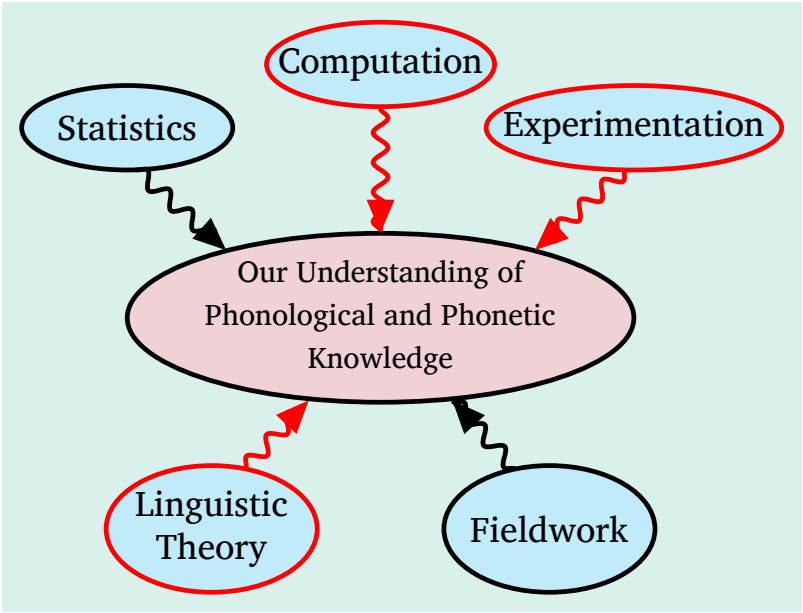


- I found that segmental representations and gestural coupling graphs were intertranslatable and the computational approach provides a way to bridge different types of representations used in the production process.

Computational Models of Production

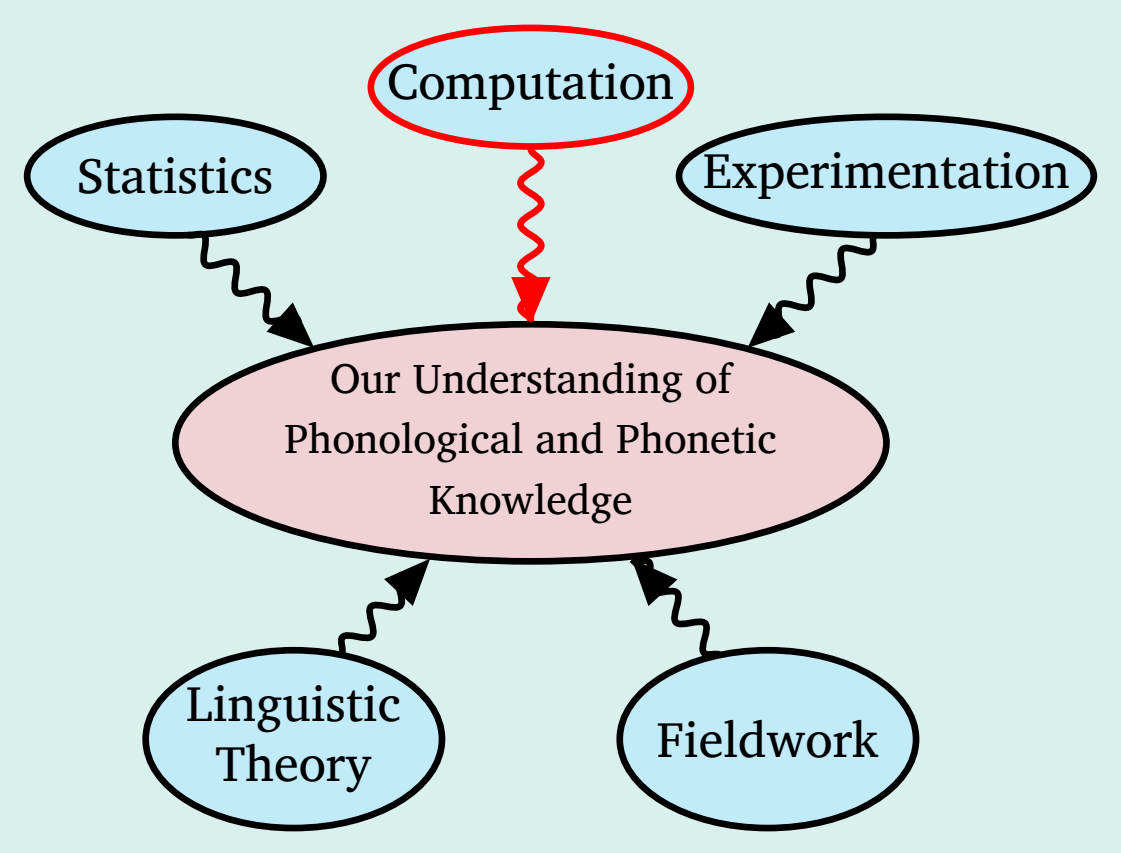
Nelson, S. and Heinz, J. (2022). Incomplete neutralization and the blueprint model of production. *Proceedings of the 2021 Annual Meeting on Phonology*.

Nelson, S. and Heinz, J. (submitted). The blueprint model of production. *Phonology*.



- The focus of today's talk!

A Multi-Faceted approach



Durvasula and Nelson (2018), Nelson and Durvasula (2021), Taherkhani et al. (in prep), Taherkhani and Nelson (accepted), Nelson (to appear), Nelson (2022), Nelson (in prep), Nelson and Heinz (2022), Nelson and Heinz (submitted)

Computational Structure

Computation

- Two definitions of **computation**:

1. The theory of computation
   - a subfield of computer science and mathematics.
   - studies what and how things can be computed using abstract computing devices.

2. Marr's computational level of analysis
   - characterizes information processing tasks in terms of the overall goal and logic of carrying out the task.

Sipser (2013); Marr (1982)

Computation

- Typed functions, a generalization of the λ-calculus (a universal model of computation) can bring together these two aspects of computation.
- $A :: B \to C$ describes a function A that maps B type things to C type things.
- An information processing device (A) takes some information (B) and processes it into something new (C).

Sipser (2013); Marr (1982); Pierce (2002); Church (1932, 1933)

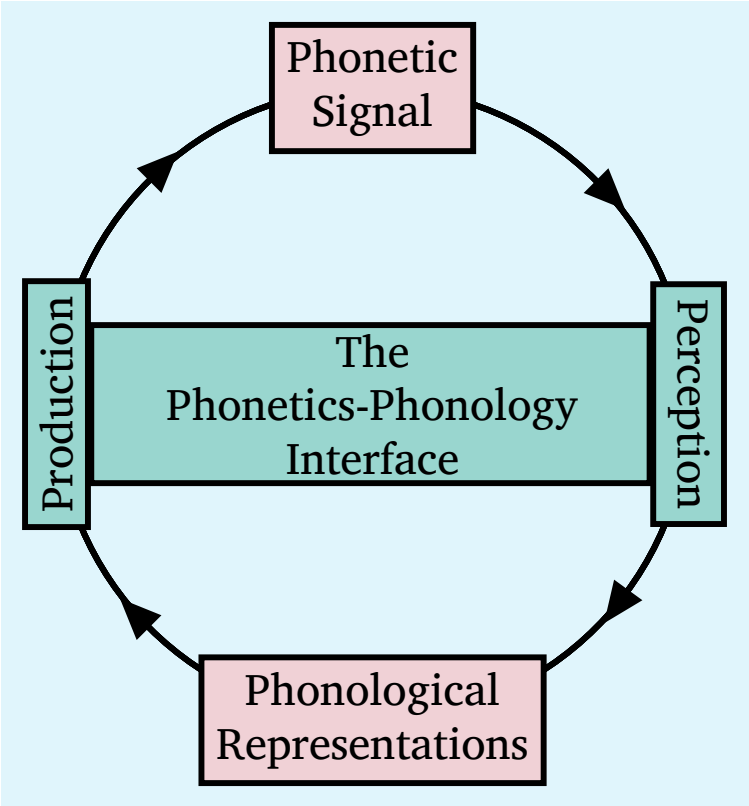
Computational *Structure*

- The typed function view gives us one half of Marr's computational level analysis of a system – abstractly, what it does.

- But recall the other half involves explaining the logic for carrying out the task.
  - I will refer to this aspect of the analysis as the computational structure.

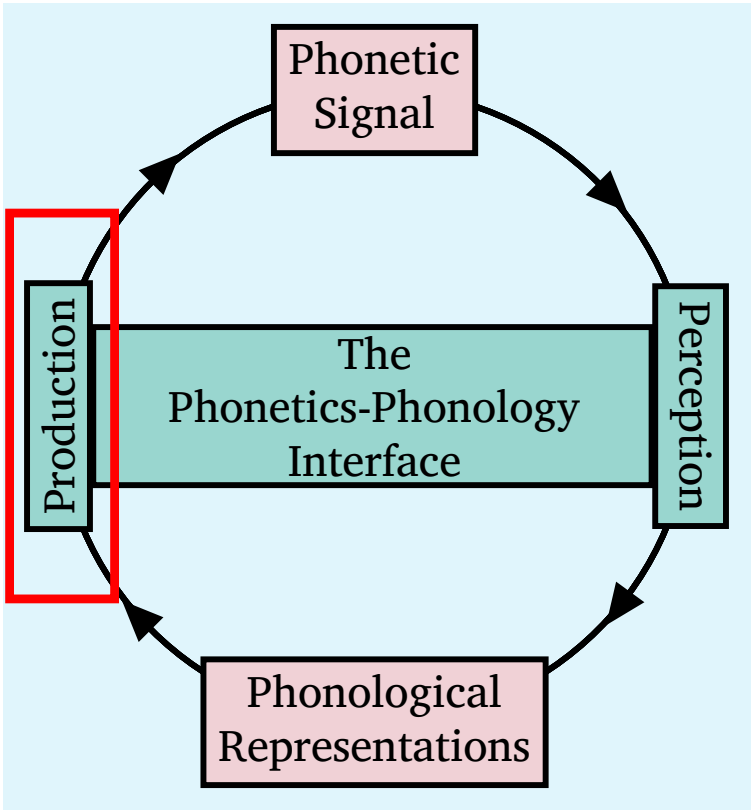
Characterizing the Interface

1. What are the properties of the *Phonological Representations PhonRep*?
2. What is the structure of the *Output/Production* function $O :: PhonRep \rightarrow PhonSig$?
3. What is the structure of the *Input/Perception* function $I :: PhonSig \rightarrow PhonRep$?



Characterizing the Interface

1. What are the properties of the *Phonological Representations PhonRep*?
2. What is the structure of the *Output/Production* function $O :: PhonRep \rightarrow PhonSig$?
3. What is the structure of the *Input/Perception* function $I :: PhonSig \rightarrow PhonRep$?



A Common View of Production

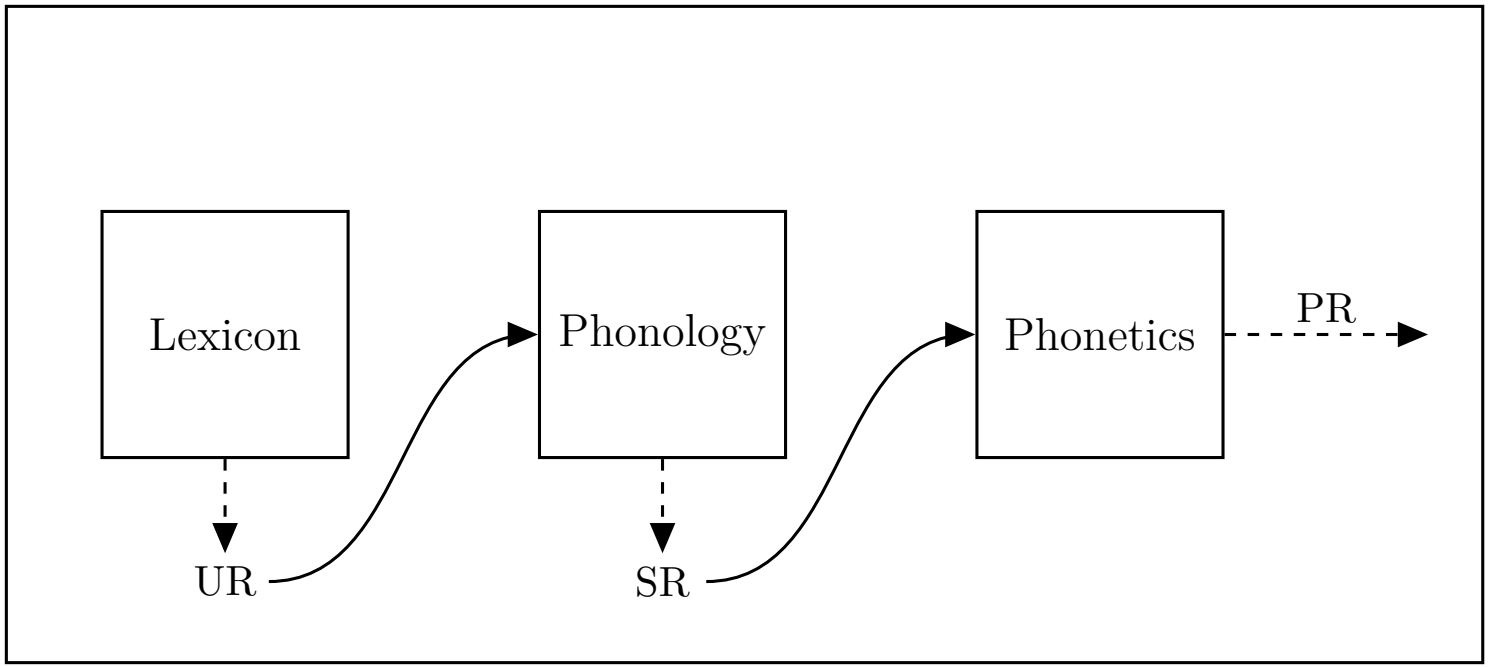
- First we do all of the phonology.
  - morphophonological alternations, allophony
- After this is completed, we take the final form and turn it into something physical.
  - gestures, acoustic targets

Modular Feed-Forward Model

- This view of the production process in generative linguistics is what is often referred to as the modular feed-forward model.

Pierrehumbert (2002); Bermúdez-Otero (2007); Kenstowicz (2010)

Modular Feed-Forward Model



Pierrehumbert (2002); Bermúdez-Otero (2007); Kenstowicz (2010)

Thinking in Functions

- As mentioned previously, typed functions allow for a top-down approach in understanding what a system (such as language production) is doing.

- Phonology is a function that maps *UR*'s to *SR*'s
  - $P :: UR \rightarrow SR$
  - "The phonology function maps *UR*s to *SR*s."
  - This is what phonology does.

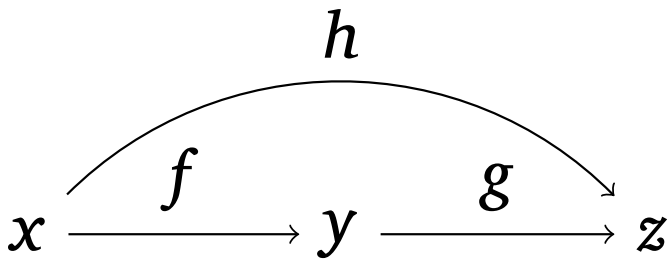
Roark and Sproat (2007), Heinz (2018)

Thinking in Functions

- The phonetics function in the modular feed-forward model has type $A_{\text{MFF}} :: SR \rightarrow PR$.
  - "The phonetics function maps *SR*s to *PR*s."
  - This is what phonetics does.

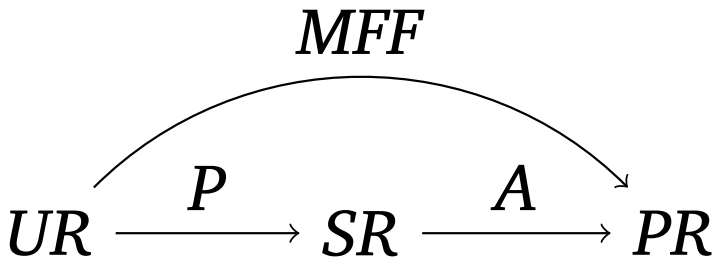
Thinking in Functions

- Two functions can be combined into one through composition.
- A function $f :: x \to y$ composed with a function $g :: y \to z$ results in the function $h :: x \to z$.



Modular Feed-Forward Model Redux

- Since phonology has the type $UR \rightarrow SR$ and phonetics has the type $SR \rightarrow PR$, the modular feed-forward model is a composed function $MFF :: UR \rightarrow PR$.
  - $A_{\text{MFF}}(P(UR)) = PR$

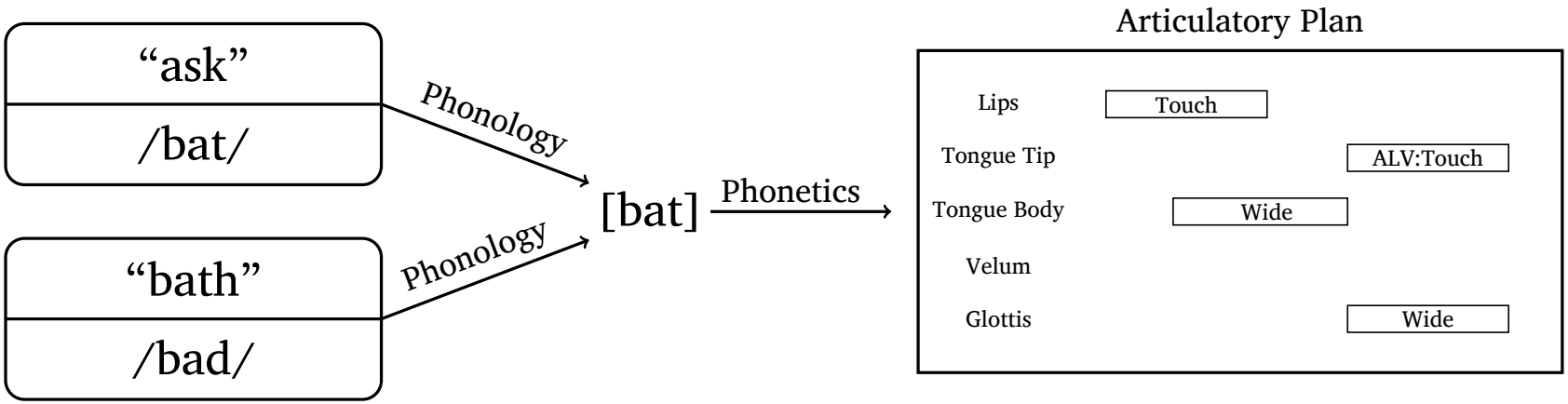


Questioning the Modular Feed-Forward Model

- Structuring the production process this way is what has lead researchers to question the validity of a traditional phonological grammar that maps discrete inputs to discrete outputs.

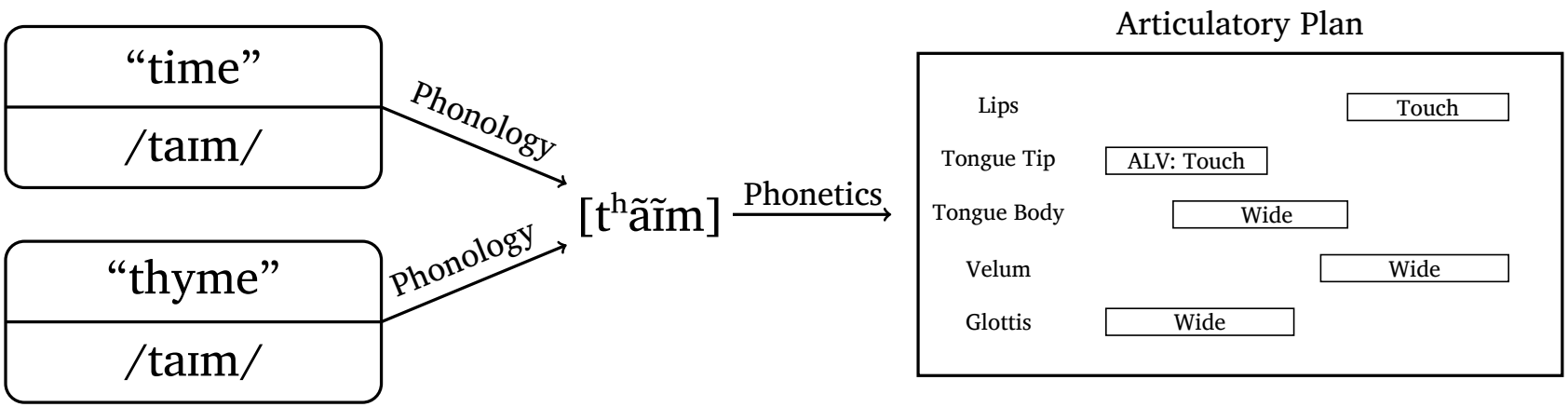
Problem 1 for the Modular Feed-forward Model

- Incomplete neutralization is a problem for the modular feed-forward model which predicts that two items with the same phonological surface form should have the same phonetic properties.



Problem 2 for the Modular Feed-forward Model

- Variation in homophone duration is a problem for the modular feed-forward model which once again predicts that two items with the same phonological surface form should have the same phonetic properties.



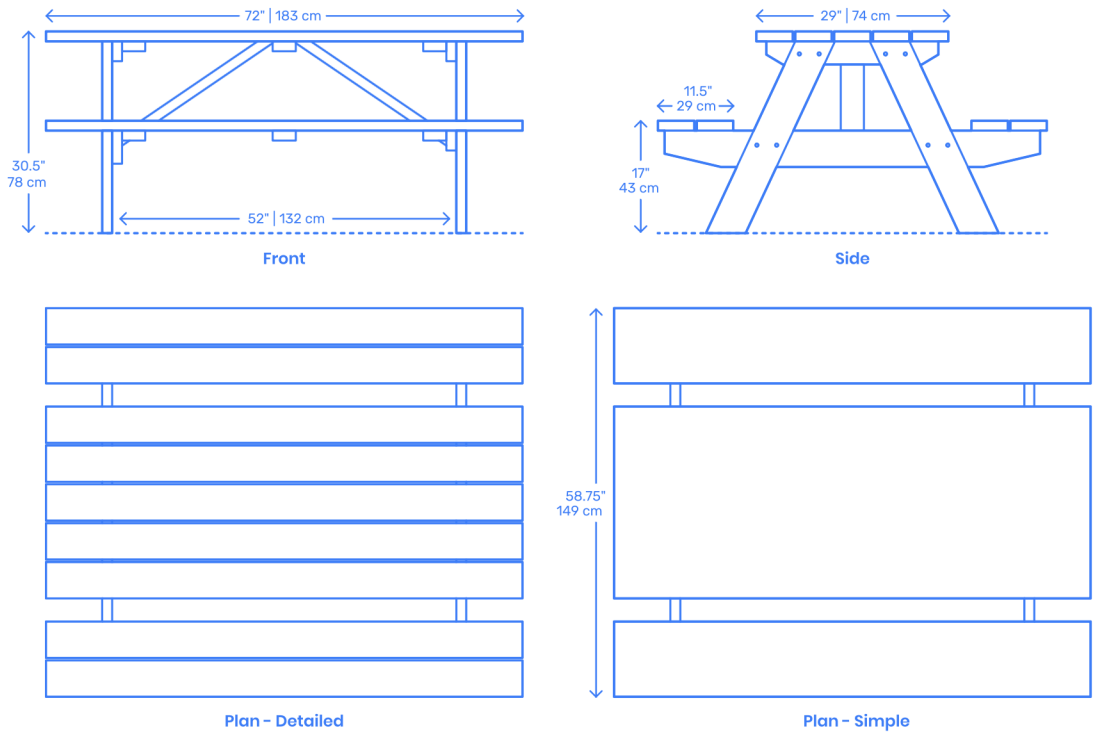
Taking a Step Back

- Our description of what a system does influences the way data is interpreted in relation to that system.
- By changing the structure of the system, it may provide a new interpretation of familiar data.

The Blueprint Model of Production

The Blueprint Model of Production

- I propose an alternative structure for the production process called the Blueprint Model of Production.



Nelson and Heinz (2022), Nelson and Heinz (submitted)

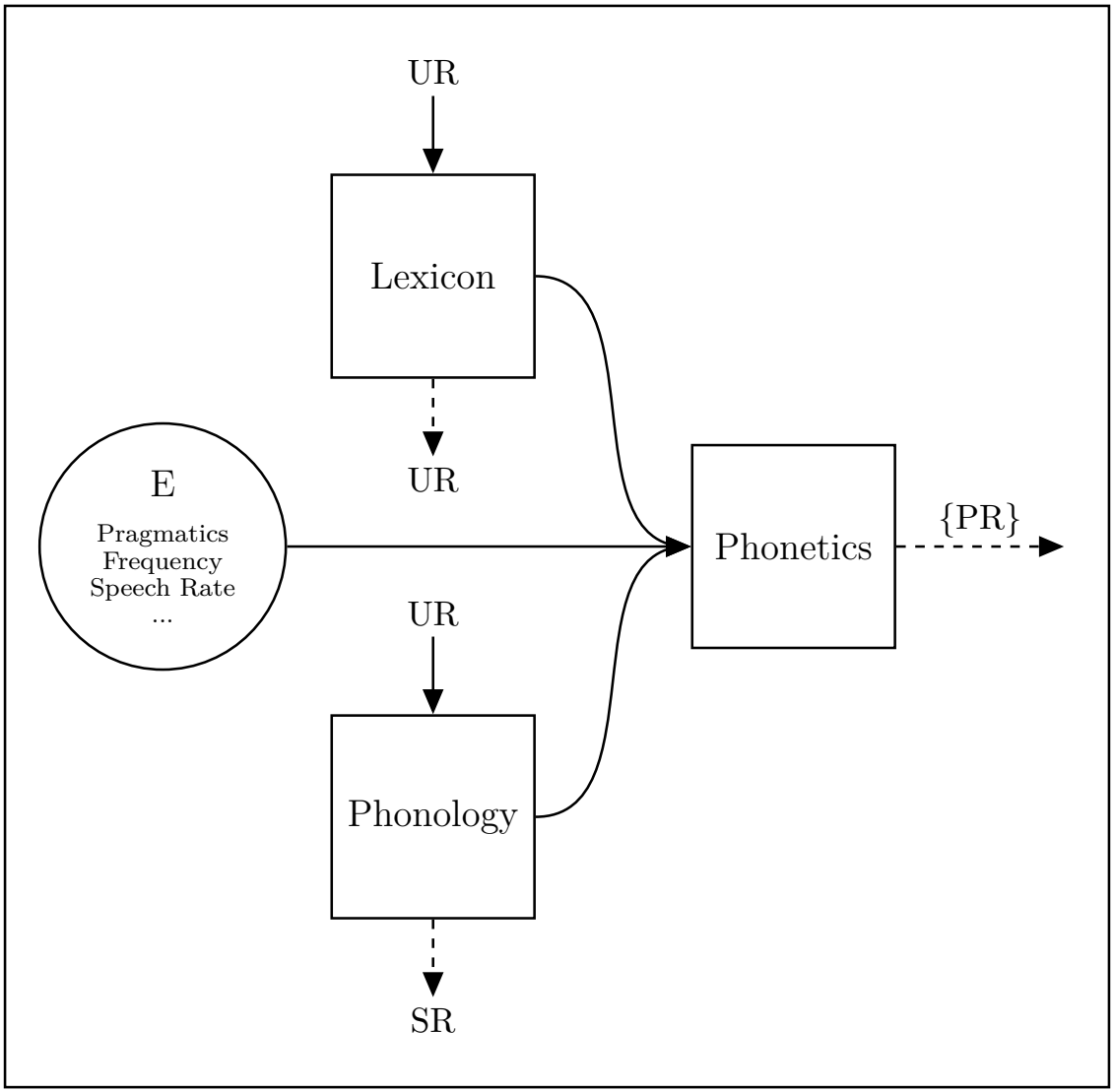
The Blueprint Model of Production

- Suppose two people use the same blueprint to build a picnic table
  1. Person A builds the table for indoor use
  2. Person B builds the table for outdoor use

- They use the same materials and same tools and end up with basically the same table.
- But Person B adds a clear coat of weatherproofing since the table will be kept outside.

- To the naked eye they're the same table! But there are subtle, fine-grained differences depending on how the table is to be used.

The Blueprint Model of Production



The Blueprint Model of Production

- The inputs to the phonetics function are the lexicon and phonology functions, as well as extra-grammatical information that influences production.
  - The lexicon is a function with type $L :: UR \rightarrow UR$.
  - Phonology is *still* a function with type $P :: UR \rightarrow SR$.
  - E is a cover type for extra-grammatical information.

- When a function takes a function as an input it is called a **higher-order function**.

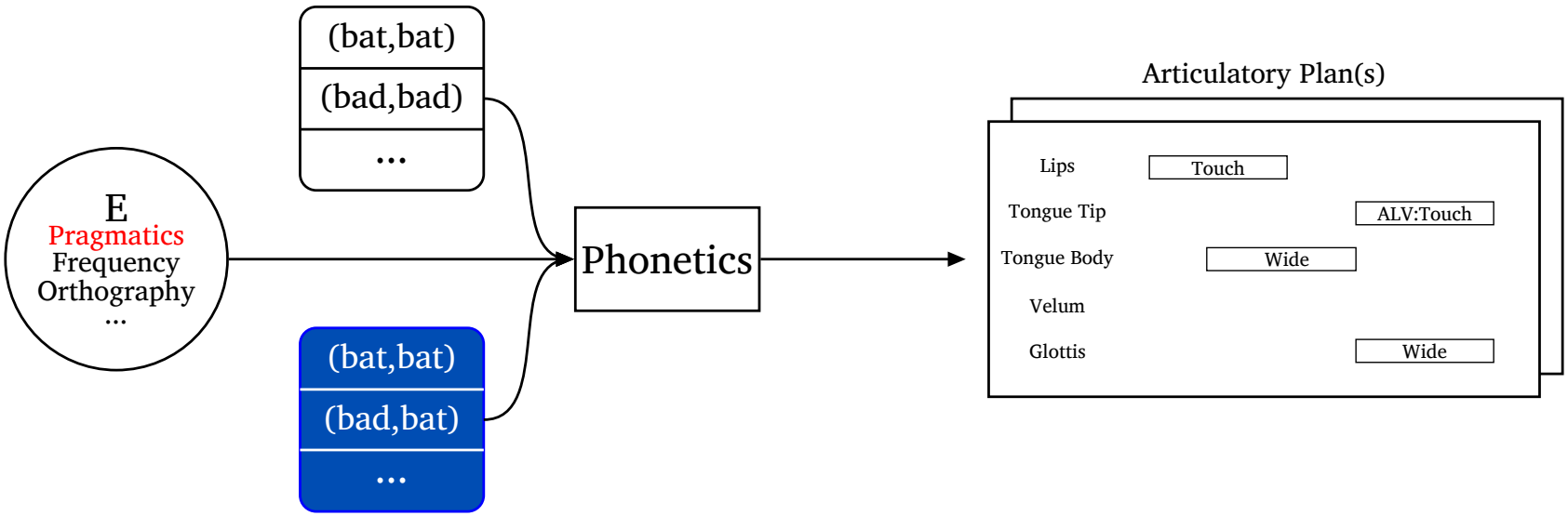
The Blueprint Model of Production

- The phonetics function in the blueprint model of production has type $A_{\text{BP}} :: L \to P \to E \to \{PR\}$.
  - "The phonetics function takes the lexicon, phonology, and extra-grammatical information and maps them to a set of phonetic representations."
  - This is what phonetics does.

  - Structuring the phonetics function in this way allows the production process access to both the underlying and surface form of a given lexical item.

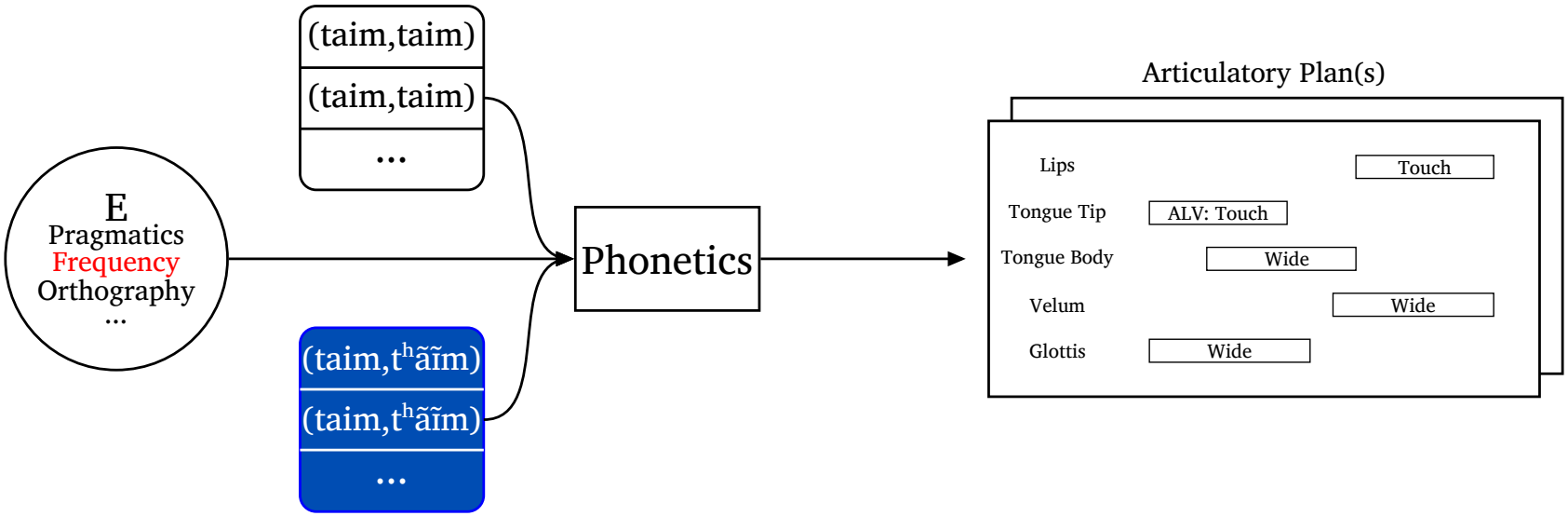
Problem 1 Is No Problem

- The blueprint model does not predict that two items with the same phonological surface form should necessarily have the same phonetic properties.



Problem 2 Is No Problem

- The blueprint model of production maintains a distinction between lexical items in the phonetics module.
- This distinction + extra-grammatical information makes variation unsurprising.



Competence and Performance

The terms "internal" and "external" evidence indicate a bias under which most phonological research is being pursued, namely, the belief that the behaviour of speakers in making acceptability judgments is somehow a more direct reflection of their linguistic knowledge than their behaviour in producing language, understanding language, etc. This bias appears to be related to the fact that linguistic knowledge is only one of the inputs to language production, language comprehension, and other forms of language performance. What accounts for the facts of performance is a conjunct of a theory of linguistic knowledge ("What is the nature of the representation of linguistic knowledge?") and a theory of language performance ("How is this knowledge put to use?").

Mohanan (1986)

Competence and Performance

The terms "internal" and "external" evidence indicate a bias under which most phonological research is being pursued, namely, the belief that the behaviour of speakers in making acceptability judgments is somehow a more direct reflection of their linguistic knowledge than their behaviour in producing language, understanding language, etc. This bias appears to be related to the fact that ***linguistic knowledge is only one of the inputs to language production, language comprehension, and other forms of language performance.*** *What accounts for the facts of performance is a conjunct of a theory of linguistic knowledge ("What is the nature of the representation of linguistic knowledge?") and a theory of language performance ("How is this knowledge put to use?").*

Mohanan (1986)

Competence and Performance

The terms "internal" and "external" evidence indicate a bias under which most phonological research is being pursued, namely, the belief that the behaviour of speakers in making acceptability judgments is somehow a more direct reflection of their linguistic knowledge than their behaviour in producing language, understanding language, etc. This bias appears to be related to the fact that linguistic knowledge is only one of the inputs to language production, language comprehension, and other forms of language performance. ***What accounts for the facts of performance is a conjunct of a theory of linguistic knowledge ("What is the nature of the representation of linguistic knowledge?") and a theory of language performance ("How is this knowledge put to use?").***

Mohanan (1986)

Simulating Incomplete Neutralization and Variation in Homophone Duration

Models vs. Simulations

- The computational level description runs into the problem of multiple realizability.
- But this is by design: the goal is to describe capacities, not specific implementations.
- The term model is used to describe higher-level architectures. Lower-level simulations can also be run by instantiating the model in specific ways, but...
- The simulations are not the model itself!

Putnam (1967), Fodor (1974), Cummins (1983), McCloskey (1991), Cooper and Guest (2014), van Rooij and Baggio (2021), Guest and Martin (2023)

Simulation Goal

- Simulations show that the structure of the Blueprint Model of Production can produce systematic continuous phonetic effects with discrete phonological knowledge.
- The goal is to simulate qualitative behavior of the system.

Simulating Incomplete Neutralization with the Blueprint Model of Production

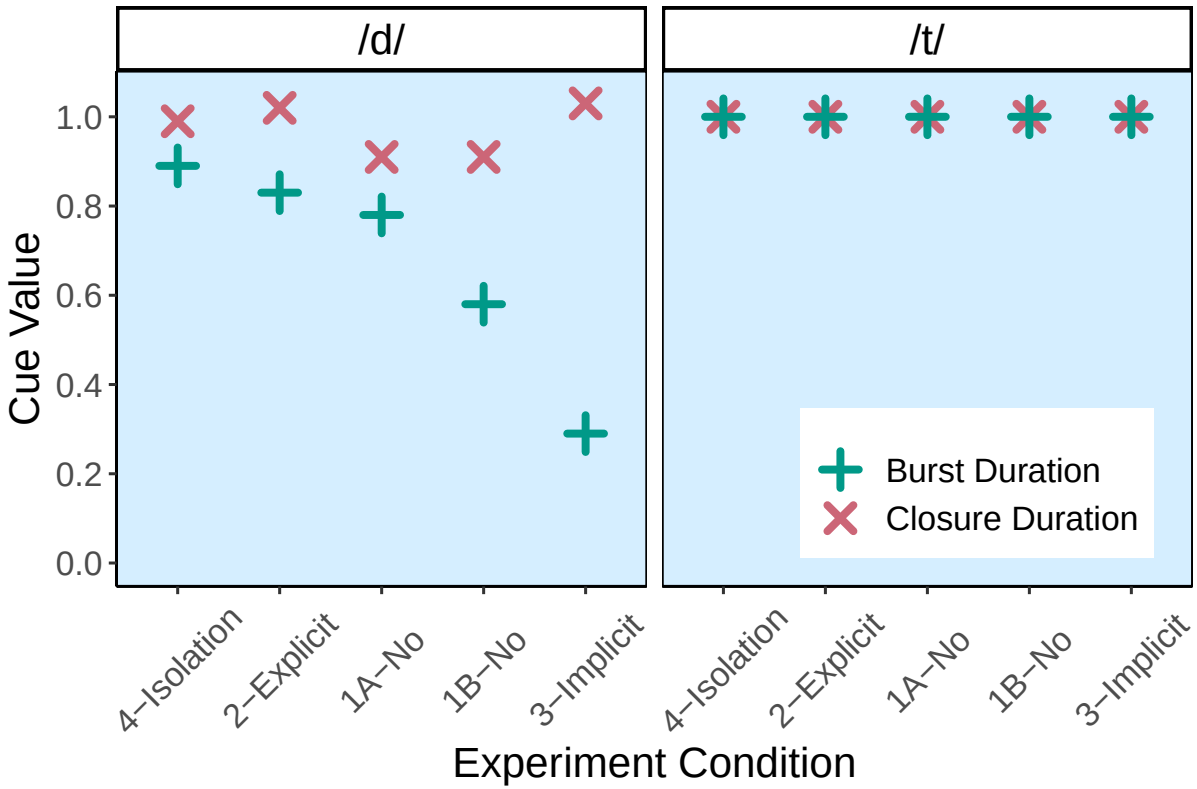
- The level of incomplete neutralization varies based on desire to maintain an underlying contrast.

1.	"... ../t/ ..." or "... ../d/ ..."	(no contrast)
2.	"I said ../t/ as in ... not ../d/ as in ..."	(explicit contrast)
3.	"I said ../t/ not ../d/"	(implicit contrast)
4.	"../t/" or "../d/"	(isolation)

- Furthermore, only a subset of all phonetic cues were incomplete.

Port and Crawford (1989)

Simulating Incomplete Neutralization with the Blueprint Model of Production



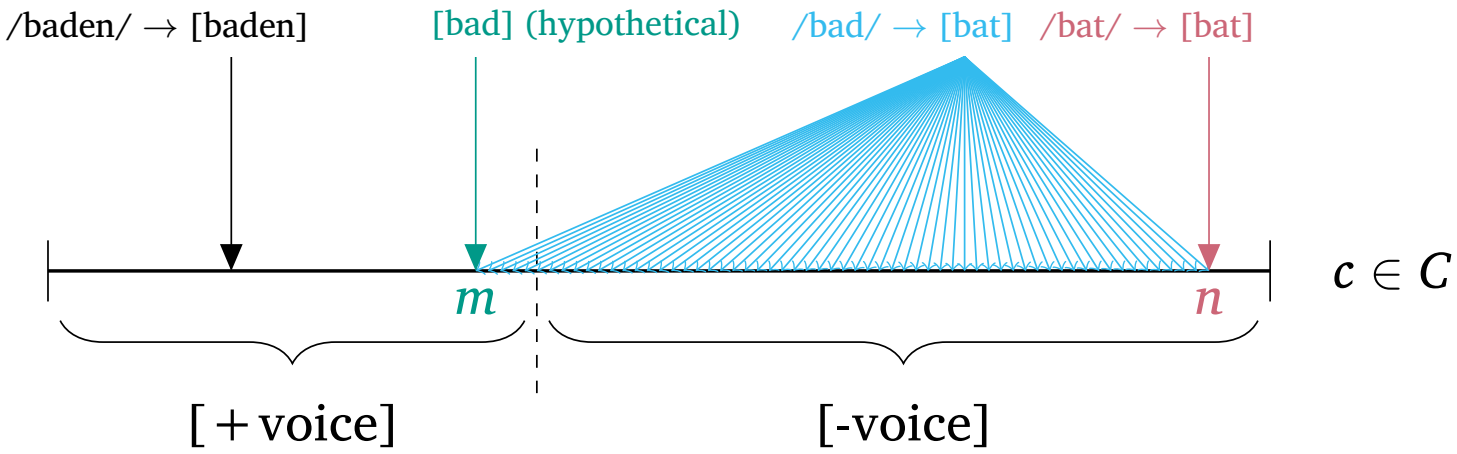
Port and Crawford (1989)

Simulating Incomplete Neutralization with the Blueprint Model of Production

- The phonetics function has access to the underlying form, surface form, as well some intent to maintain the underlying form given pragmatic context (E).

- It is therefore possible to define a function that scales how much influence the UR and SR have on the phonetic form given the pragmatic context.

Simulating Incomplete Neutralization with the Blueprint Model of Production



- [voice] feature maps to different values for cue $c \in C$ depending on position.
- [-voice] in final position maps to value n.
- [+voice] in final position maps to value m.
- The phonetic realization of /bad/→[bat] is therefore some value v where $m \leq v \leq n$.

Simulating Incomplete Neutralization with the Blueprint Model of Production

- What might a scaling formula include?
  - c_{UR} = cue value based on UR (m)
  - c_{SR} = cue value based on SR (n)
  - $i \in [0, 1]$ = intent to maintain underlying contrast
- Example scaling formulae.
  - Linear: $c = c_{UR} \times i + c_{SR} \times (1 - i)$
  - Exponential: $c = c_{UR} \times i^{\alpha} + c_{SR} \times (1 - i)^{\alpha}$
- Exponential scaling accounts for the small phonetic differences and allows for speakers to potentially produce UR-like tokens, but only in extreme scenarios.

Simulating Incomplete Neutralization with the Blueprint Model of Production

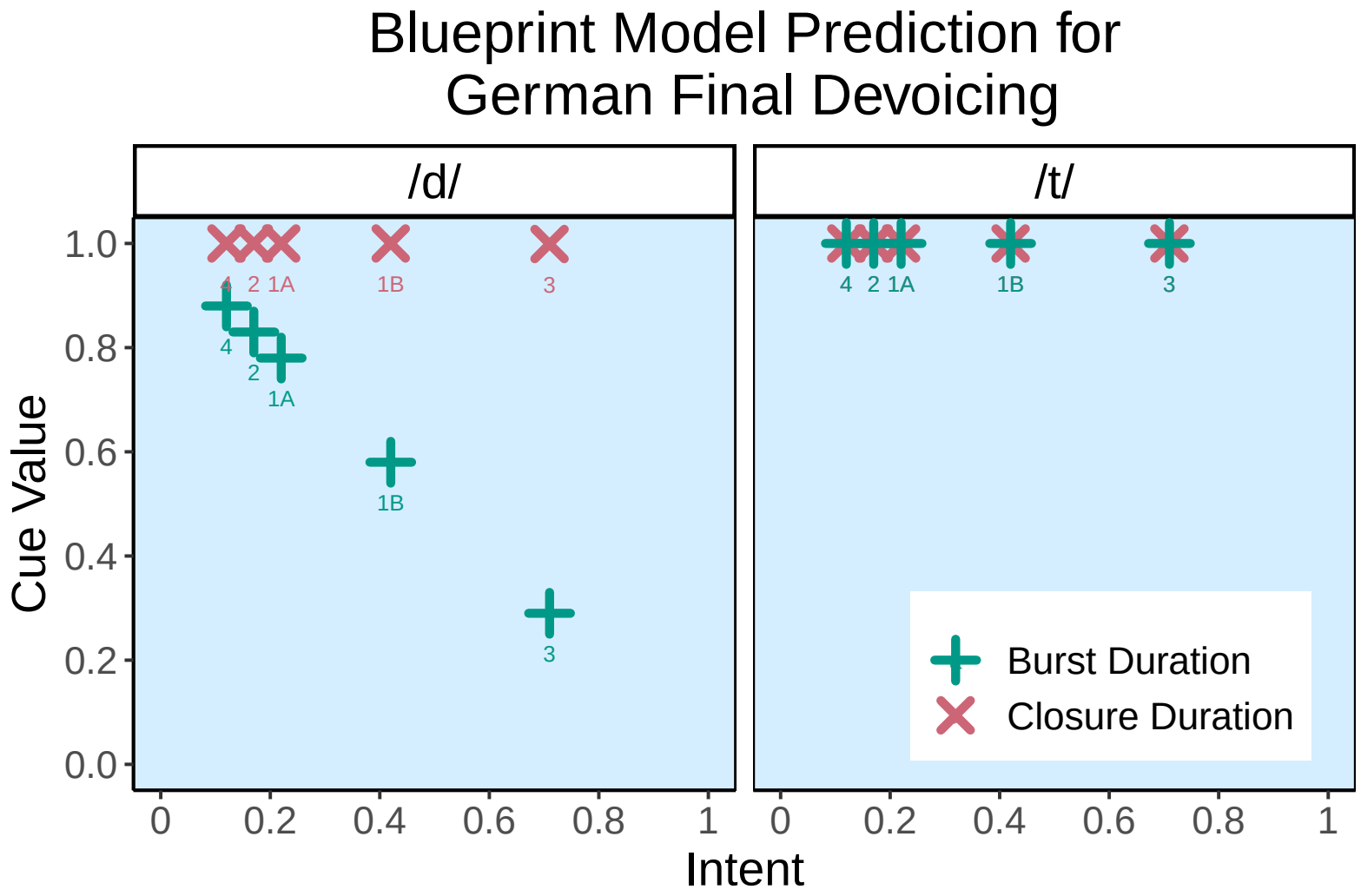
$c_{UR/SR}$ is 1 for t and 0 for d

$$c = c_{UR} \times i^{\alpha} + c_{SR} \times (1 - i)^{\alpha}$$

i values estimated based on pragmatic context

High α for cues that don't vary; Low α for those that do

Simulating Incomplete Neutralization with the Blueprint Model of Production



Simulating Incomplete Neutralization with the Blueprint Model of Production

- Final devoicing in German is not the only data that can be simulated this way.
  - Tonal Near Merger in Cantonese
  - Vowel Epenthesis in Lebanese Arabic

Yu (2007); Gouskova and Hall (2009); Hall (2013)

Simulating Incomplete Neutralization with the Blueprint Model of Production

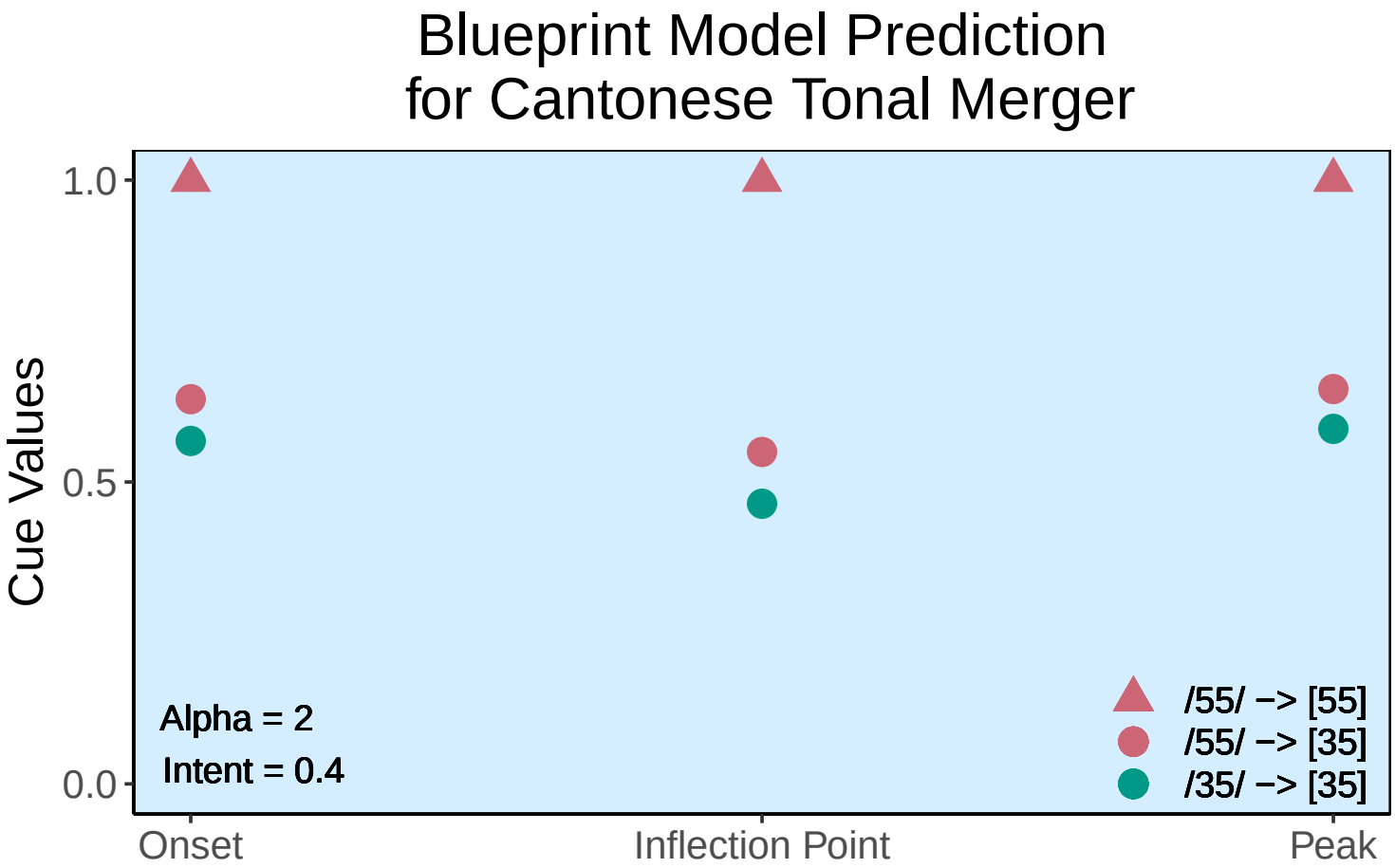
- In Cantonese, the morphemes /tsɔ/ and /tɐkˉ/ both surface with a mid-rising tone in contracted syllables:
  1. /paŋ22 tsɔ35/ → [pɔ35] 'to weigh (PERF)'
  2. /pɔŋ22 tɐkˉ55/ → [pɔ35] 'to weigh (POTENTIAL)

- The mid-rising tone derived from underlying high tone was statistically higher at all measured points than the faithful surface mid-rising tone, but not perceptible to listeners.

- *"Thus, the extra-high f0 of the [derived mid-rising tone] can be interpreted as the retention of the tonal profile of an underlying [high] tone."*

Yu (2007)

Simulating Incomplete Neutralization with the Blueprint Model of Production



Simulating Incomplete Neutralization with the Blueprint Model of Production

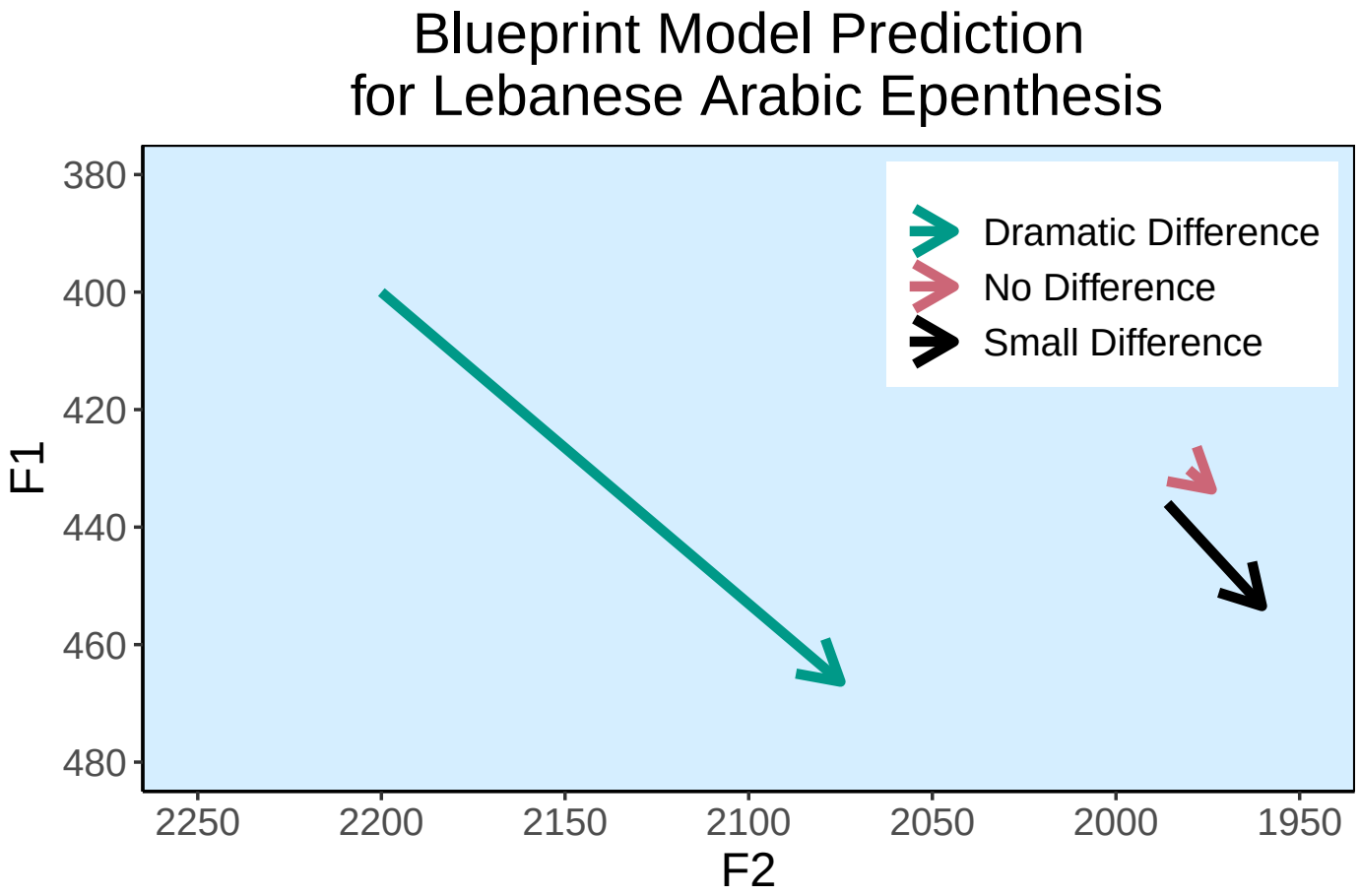
- In Lebanese Arabic, speakers epenthesize an [i] vowel to break up word final CC clusters. This results in neutralization with lexical items ending in CiC.
  1. /libs/ → [libis] 'clothes'
  2. /libis/ → [libis] 'wore'

- Epenthetic [i] has shorter duration and a lower F2 (more back). Sometimes it is perceptible, sometimes it is not.

- *"...epenthesis introduces something less than an [i]: the vowel is backer and shorter, all properties that would make this vowel closer to [ɨ] or [ə] – and, arguably, to zero."*

Gouskova and Hall (2009); Hall (2013)

Simulating Incomplete Neutralization with the Blueprint Model of Production



- Three types of speakers: dramatic difference, small difference, no difference.
- UR target is a neutral configuration with 0 duration and SR target is [i].
- Different intent values for different types of speakers.

Where we stand

- The simulations so far show that the data from Problem 1 can be simulated using the architecture of the Blueprint Model of Production and a discrete phonology.
- What about Problem 2?

Simulating Variation in Homophone Duration with the Blueprint Model of Production

- The phonetics function has access to the underlying form, surface form, as well as information about frequency (E).
- It is therefore possible to define a function that scales the phonetic form based on frequency information.

Simulating Variation in Homophone Duration with the Blueprint Model of Production

- How might this be implemented?
- $PR_{duration} = duration_{target}(SR) + \delta(frequency(LI))$
  - $duration_{target}$ is determined by the surface phonological form.
  - δ provides an offset based on frequency.
  - *frequency* is determined by the lexical item (*LI*).

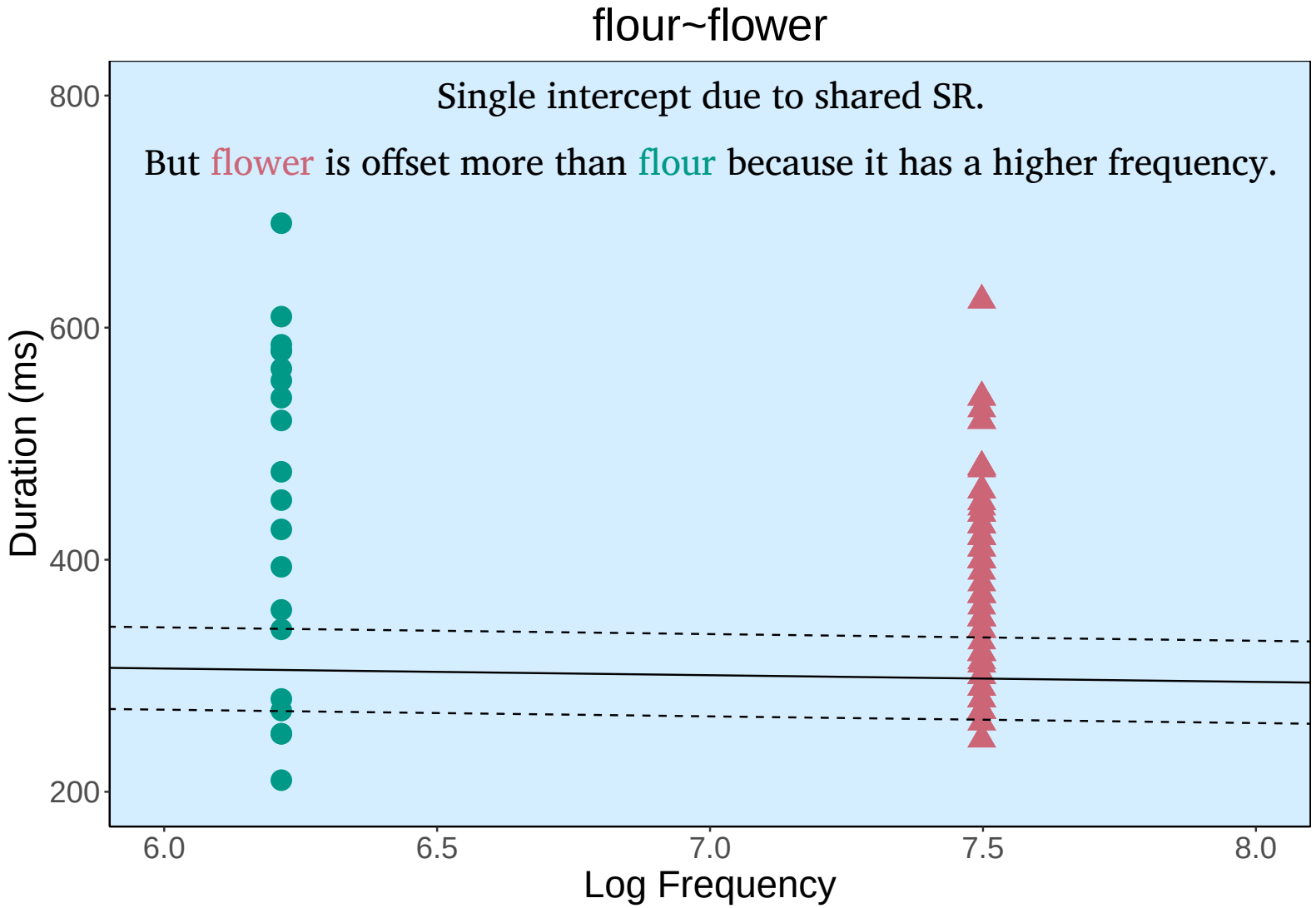
Simulating Variation in Homophone Duration with the Blueprint Model of Production

This function can be implemented as a linear model

$$PR_{duration} = \overbrace{duration_{target}(SR) + \delta(frequency(LI))}$$

$$\hat{y} = \underbrace{\beta_0 + \beta_i \times [SR_i = SR(x)]}_{\text{varying intercepts based on surface phonological form}} + \underbrace{\beta_1 \times frequency(LI(x))}_{\text{Single slope based on frequency of lexical item}}$$

Simulating Variation in Homophone Duration with the Blueprint Model of Production



Summary and Future Directions

Summary

- The Blueprint Model of Production is a computational description of the structure of the phonetics-phonology interface.

- Simulations of the blueprint model of production with discrete phonological knowledge show that it can predict behavior previously thought to be problematic for discrete theories of phonology.

- Phenomena like incomplete neutralization and variation in homophone duration are not arguments against formal/discrete phonology overall. That reasoning only holds if we assume the modular feed-forward characterization of the interface.

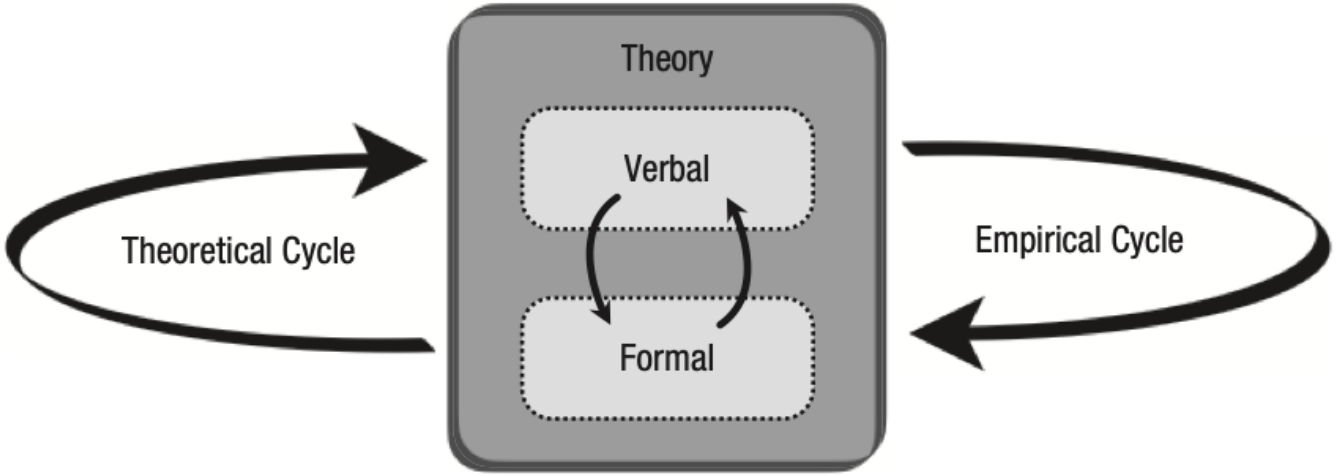
Causal Inference and Auxilary Assumptions

- Duhem-Quine Thesis:
  - When experimentally testing a scientific hypothesis, it is impossible to know if the reason the results don't match the theory is because the theory is wrong or if some unspoken auxiliary assumption is wrong.

- Empirical data on incomplete neutralization and variation in homophone duration are argued to be incompatible with a discrete and formal theory of phonology, but these claims have been made without consideration of the structure of the phonetics-phonology interface.

Quine (1951), Duhem (1954), Lakatos (1970)

Future Directions



- The Blueprint Model is a response to an experimental cycle dominated by the Modular Feed-forward Model.
- This is a step towards a new theoretical cycle which in turn can lead to a new experimental cycle.

---

van Rooij and Baggio (2021)

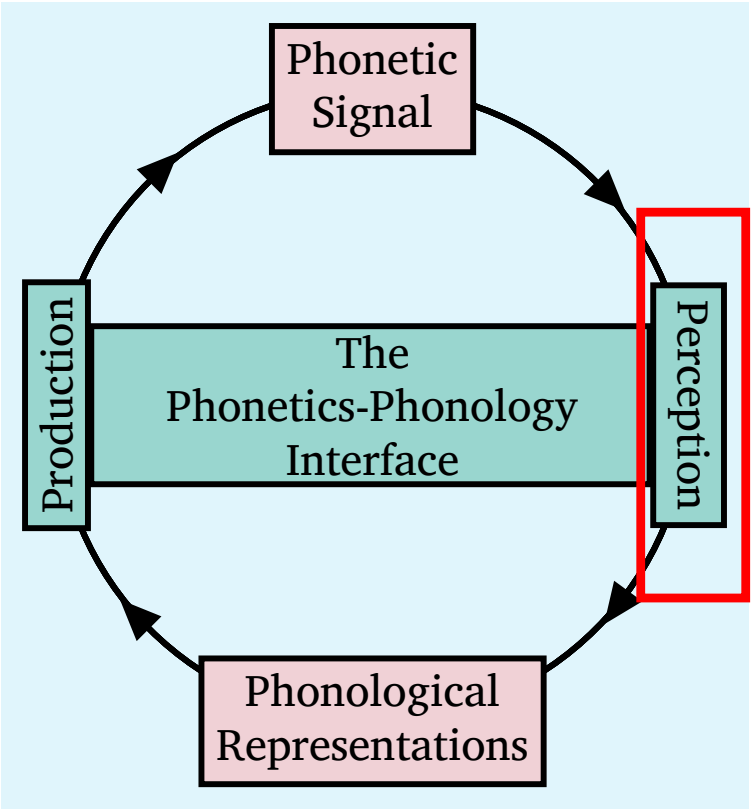
Future Directions

- There is plenty of work left to do in terms of the theoretical cycle and the Blueprint Model of Production.

- Empirical Phenomena:
  - Deletion
  - Optionality
  - Boundary Effects
  - Absolute Neutralization
  - ...

- There are also questions about computational complexity and the functions proposed.

Future Directions



- Is there a parallel Blueprint Model of Perception?

Takeaway Message

Phonetic Production Data $\Rightarrow$ Non-categorical Phonology

Takeaway Message

~~Phonetic Production Data~~ $\Rightarrow$ ~~Non-categorical Phonology~~

Phonetic Production Data
+
MFF Model of Interface

$\Rightarrow$ Non-categorical Phonology

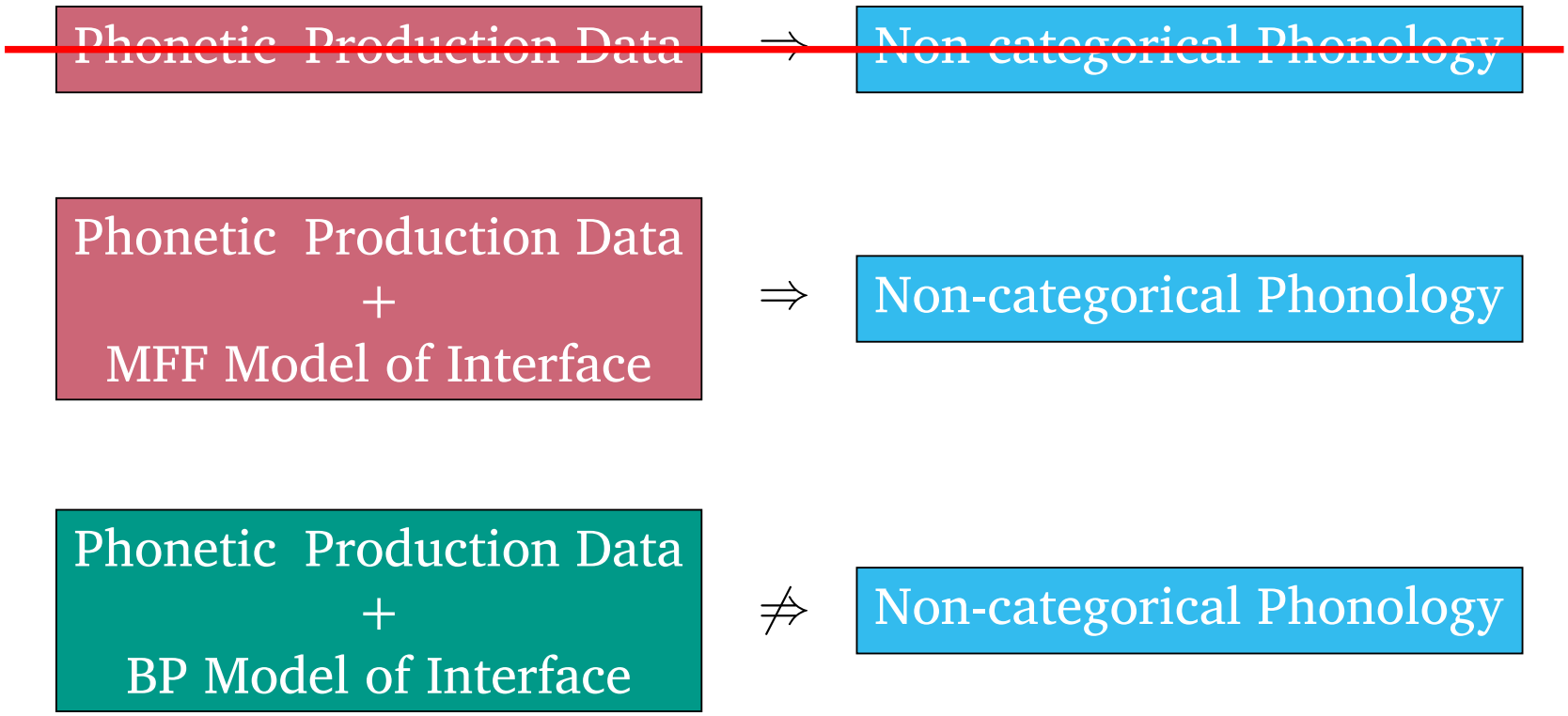
Takeaway Message

~~Phonetic Production Data~~ $\Rightarrow$ ~~Non-categorical Phonology~~

Phonetic Production Data + MFF Model of Interface $\Rightarrow$ Non-categorical Phonology

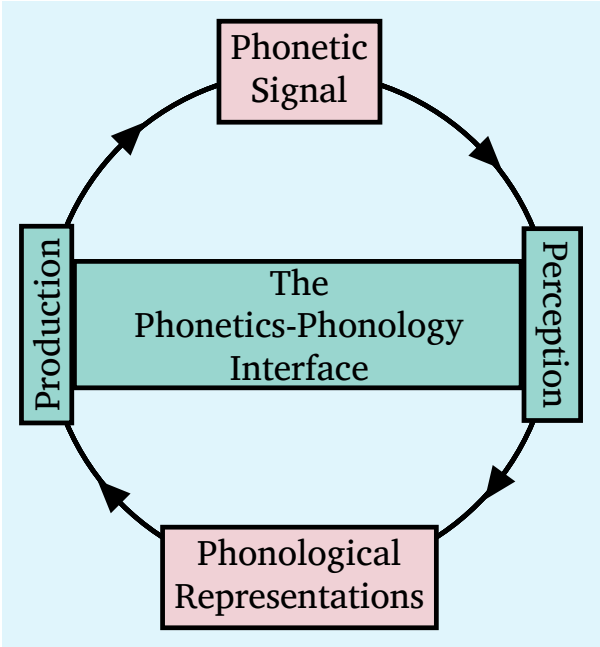
Phonetic Production Data + BP Model of Interface $\not\Rightarrow$ Non-categorical Phonology

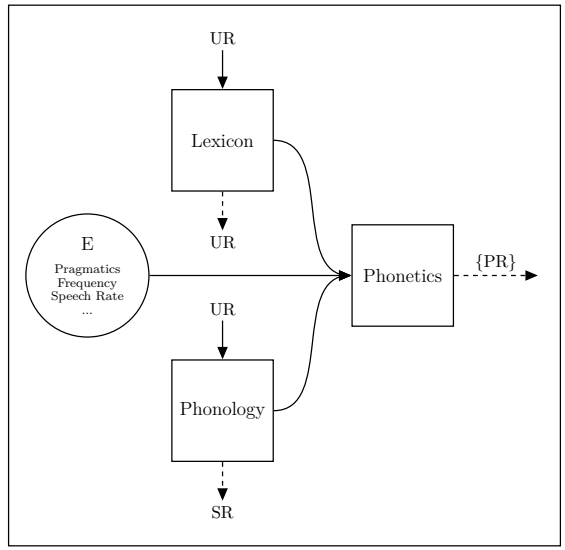
Takeaway Message

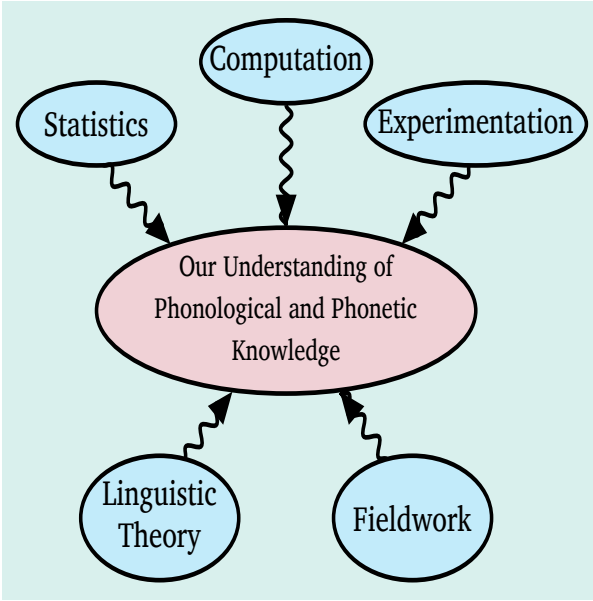


- A computational approach helps make clear that the structure of the interface has consequences for our theories of phonology and how we interpret data in relation to said theories.

Thank You!


Phonetic Signal
Production
The Phonetics-Phonology Interface
Perception
Phonological Representations


UR
Lexicon
UR
E
Pragmatics
Frequency
Speech Rate
...
Phonetics
{PR}
UR
Phonology
SR


Computation
Statistics
Experimentation
Our Understanding of Phonological and Phonetic Knowledge
Linguistic Theory
Fieldwork

Bibliography I

Albright, A. and Hayes, B. (2006). Modelling productivity with the gradual learning algorithm: The problem of accidentally exceptionless generalizations. In Fanselow, G., Féry, C., Schlesewsky, M., and Vogel, editors, Gradience in Grammar. Oxford University Press.

Bell, A., Brenier, J. M., Gregory, M., Girand, C., and Jurafsky, D. (2009). Predictability effects on durations of content and function words in conversational english. Journal of Memory and Language, 60(1):92–111.

Bermúdez-Otero, R. (2007). Diachronic phonology. In de Lacy, P., editor, The Cambridge handbook of phonology, pages 497–517. Cambridge.

Bybee, J. (2001). Phonology and language use, volume 94. Cambridge University Press.

Chomsky, N. and Halle, M. (1968). The sound pattern of English. ERIC.

Church, A. (1932). A set of postulates for the foundation of logic. Annals of mathematics, pages 346–366.

Church, A. (1933). A set of postulates for the foundation of logic. Annals of mathematics, pages 839–864.

Coetzee, A. W. and Pater, J. (2008). Weighted constraints and gradient restrictions on place co-occurrence in muna and arabic. Natural Language & Linguistic Theory, 26:289–337.

Coleman, J. and Pierrehumbert, J. (1997). Stochastic phonological grammars and acceptability. In Computational Phonology: Third Meeting of the ACL Special Interest Group in Computational Phonology.

Cooper, R. P. and Guest, O. (2014). Implementations are not specifications: Specification, replication and experimentation in computational cognitive modeling. Cognitive Systems Research, 27:42–49.

Cummins, R. (1983). The Nature of Psychological Explanation. MIT Press.

Dinnsen, D. and Garcia-Zamor, M. (1971). The three degrees of vowel length in German. Research on Language & Social Interaction, 4(1):111–126.

Dinnsen, D. A. and Charles-Luce, J. (1984). Phonological neutralization, phonetic implementation and individual differences. Journal of phonetics, 12(1):49–60.

Dmitrieva, O., Jongman, A., and Sereno, J. (2010). Phonological neutralization by native and non-native speakers: The case of Russian final devoicing. Journal of phonetics, 38(3):483–492.

Bibliography II

Du, N. and Durvasula, K. (2024). Phonetically incomplete neutralisation can be phonologically complete: evidence from huai'an mandarin. Phonology, pages 1–37.

Duhem, P. M. M. (1954). The Aim and Structure of Physical Theory. Princeton University Press.

Durvasula, K. and Nelson, S. (2018). Lexical retuning targets features. In Gallagher, G., Gouskova, M., and Yin, S., editors, Proceedings of the 2017 Annual Meeting on Phonology.

Ernestus, M. (2011). Gradience and categoricality in phonological theory. In The Blackwell companion to phonology, pages 2115–2136. Wiley-Blackwell.

Flemming, E. (2001). Scalar and categorical phenomena in a unified model of phonetics and phonology. Phonology, 18(1):7–44.

Fodor, J. A. (1974). Special sciences, (or: the disunity of science as a working hypothesis). Synthese, 28:97–115.

Fosler-Lussier, E. and Morgan, N. (1998). Effects of speaking rate and word frequency on conversational pronunciations. In Modeling Pronunciation Variation for Automatic Speech Recognition.

Fourakis, M. and Iverson, G. K. (1984). On the 'incomplete neutralization' of German final obstruents. Phonetica, 41(3):140–149.

Gahl, S. (2008). Time and thyme are not homophones: The effect of lemma frequency on word durations in spontaneous speech. Language, 84(3):474–496.

Gouskova, M. and Hall, N. (2009). Acoustics of epenthetic vowels in Lebanese Arabic. Phonological argumentation: Essays on evidence and motivation, pages 203–225.

Guest, O. and Martin, A. E. (2023). On logical inference over brains, behaviour, and artificial neural networks. Computational Brain & Behavior, pages 1–15.

Hall, N. (2013). Acoustic differences between lexical and epenthetic vowels in lebanese arabic. Journal of Phonetics, 41(2):133–143.

Halle, M. (2003). From memory to speech and back. De Gruyter Mouton.

Heinz, J. (2018). The computational nature of phonological generalizations. In Hyman, L. and Plank, F., editors, Phonological Typology, Phonetics and Phonology, chapter 5, pages 126–195. De Gruyter Mouton.

Bibliography III

Jakobson, R., Fant, C. G., and Halle, M. (1951). Preliminaries to speech analysis: The distinctive features and their correlates. MIT press.

Jassem, W. and Richter, L. (1989). Neutralization of voicing in Polish obstruents. Journal of Phonetics, 17(4):317–325.

Jurafsky, D., Bell, A., Gregory, M., and Raymond, W. D. (2001). Probabilistic relations between words: Evidence from reduction in lexical production. In Bybee, J. and Hopper, P., editors, Frequency and the emergence of linguistic structure, pages 229–254. John Benjamins.

Kenstowicz, M. (2010). The cambridge handbook of phonology. Language, 86(1):216–219.

Kharlamov, V. (2014). Incomplete neutralization of the voicing contrast in word-final obstruents in Russian: Phonological, lexical, and methodological influences. Journal of Phonetics, 43:47–56.

Kingston, J. (2019). The interface between phonetics and phonology. The Routledge handbook of phonetics, pages 359–400.

Lakatos, I. (1970). Falsification and the Methodology of Scientific Research Programmes, volume 4, page 91–196. Cambridge University Press.

Leslau, W. (1969). Frequency as determinant of linguistic changes in the Ethiopian languages. Word, 25(1-3):180–189.

Lionnet, F. (2017). A theory of subfeatural representations: the case of rounding harmony in Laal. Phonology, 34(3):523–564.

Losiewicz, B. (1995). Word frequency effects on the acoustic duration of morphemes. Journal of the Acoustic Society of America, 97:32–43.

Marr, D. (1982). Vision: A computational investigation into the human representation and processing of visual information. CUMINCAD.

McCarthy, J. J. (2003). Ot constraints are categorical. Phonology, 20(1):75–138.

McCloskey, M. (1991). Networks and theories: The place of connectionism in cognitive science. Psychological science, 2(6):387–395.

Mohanan, K. P. (1986). The theory of lexical phonology, volume 6. Springer Science & Business Media.

Nelson, S. (2022). A model theoretic perspective on phonological feature systems. Proceedings of the Society for Computation in Linguistics, 5(1).

Bibliography IV

Nelson, S. (in prep). Inferring linear order from non-linear gestural representations.

Nelson, S. (to appear). Process interaction and complexity. In Heinz, J., editor, Doing Computational Phonology.

Nelson, S. and Durvasula, K. (2021). Lexically-guided perceptual learning does generalize to new phonetic contexts. Journal of Phonetics, 84:101019.

Nelson, S. and Heinz, J. (2022). Incomplete neutralization and the blueprint model of production. In Jurgec, P., Duncan, L., Elfner, E., Kang, Y., Kochetov, A., O'Neill, B. K., Ozburn, A., Rice, K., Sanders, N., Schertz, J., Shaftoe, N., and Sullivan, L., editors, Proceedings of the 2021 Annual Meeting on Phonology.

Nelson, S. and Heinz, J. (submitted). The blueprint model of production.

Pierce, B. C. (2002). Types and programming languages. MIT press.

Pierrehumbert, J. (2002). Word-specific phonetics. Laboratory phonology, 7.

Port, R. and Crawford, P. (1989). Incomplete neutralization and pragmatics in German. Journal of phonetics, 17:257–282.

Port, R., Mitleb, F., and O'Dell, M. (1981). Neutralization of obstruent voicing in German is incomplete. The journal of the Acoustical Society of America, 70(S1):S13–S13.

Port, R. F. and Leary, A. P. (2005). Against formal phonology. Language, 81(4):927–964.

Port, R. F. and O'Dell, M. L. (1985). Neutralization of syllable-final voicing in German. Journal of phonetics.

Putnam, H. (1967). Psychological predicates. In Capitan, W. H. and Merill, D. D., editors, Art, mind, and religion, pages 37–48. University of Pittsburgh Press.

Quine, W. V. O. (1951). Two dogmas of empiricism. Philosophical Review, 60(1):20–43.

Reiss, C. and Volenec, V. (2020). Conquer primal fear: Phonological features are innate and substance-free. https://ling.auf.net/lingbuzz/005683.

Roark, B. and Sproat, R. (2007). Computational approaches to morphology and syntax, volume 4. Oxford University Press.

Shrager, M. (2012). Neutralization of word-final voicing in Russian. Journal of Slavic linguistics, pages 71–99.

Sipser, M. (2013). Introduction to the Theory of Computation. Course Technology.

Bibliography V

Slowiaczek, L. M. and Dinnsen, D. A. (1985). On the neutralizing status of Polish word-final devoicing. Journal of phonetics.

Smolensky, P. and Goldrick, M. (2016). Gradient symbolic representations in grammar: The case of French liaison. Ms. Johns Hopkins University and Northwestern University. Available as ROA, 1286.

Taherkhani, N. and Nelson, S. (accepted). Southern Tati: Takestani Dialect. Journal of the International Phonetic Association.

Taherkhani, N., Nelson, S., and Heinz, J. (in prep). A Contrastive Hierarchy for Vowels in Southern Tati: Takestani Dialect.

van Rooij, I. and Baggio, G. (2021). Theory before the test: How to build high-verisimilitude explanatory theories in psychological science. Perspectives on Psychological Science.

Van Rooy, B., Wissing, D., and Paschall, D. D. (2003). Demystifying incomplete neutralisation during final devoicing. Southern African Linguistics and Applied Language Studies, 21(1-2):49–66.

Walsh, T. and Parker, F. (1983). The duration of morphemic and nonmorphemic /s/ in English. Journal of Phonetics, 11:201–206.

Warner, N., Good, E., Jongman, A., and Sereno, J. (2006). Orthographic vs. morphological incomplete neutralization effects. Journal of Phonetics, 34(2):285–293.

Warner, N., Jongman, A., Sereno, J., and Kemps, R. (2004). Incomplete neutralization and other sub-phonemic durational differences in production and perception: Evidence from Dutch. Journal of phonetics, 32(2):251–276.

Yu, A. C. (2007). Understanding near mergers: The case of morphological tone in Cantonese. Phonology, 24(1):187–214.