Artificial Language Learning: More than Transitional Probabilities?

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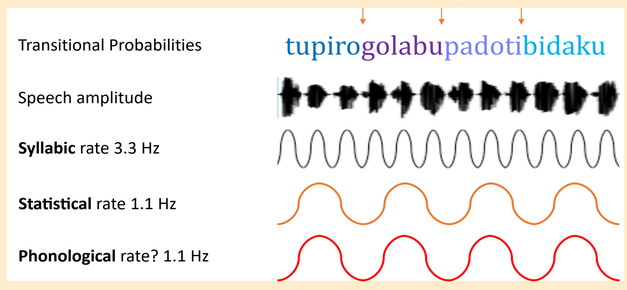
Introduction

Statistical Learning

- *Statistical Learning* (SL) = Ability to extract statistical regularities and learn from the environment
- *Transitional Probabilities* (TPs) = Forward conditional probability of syllables in a stream → used to infer and learn new words [1]
- *Neural-Frequency-Tagging* (NFT) → Cortical tacking of repetitive TP patterns associates with speech chunking [2-6]

Neural-Frequency-Tagging



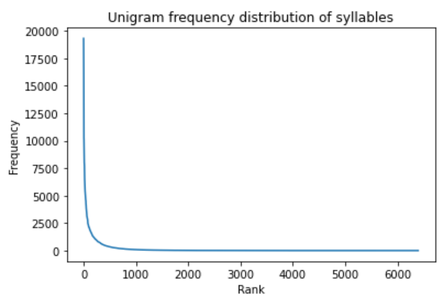
Speech Tracking

- **Confounds**: Differences in phoneme and syllable probabilities in the language, phonotactics, phonological patterns and acoustic-spectral differences limit the interpretability of SL findings [6-8].
- Cortical tracking at the word rate can emerge from statistical or phonological rhythms if they are both ”tagged” at the same rate
- **How to isolate TPs and eliminate all confounding factors?**

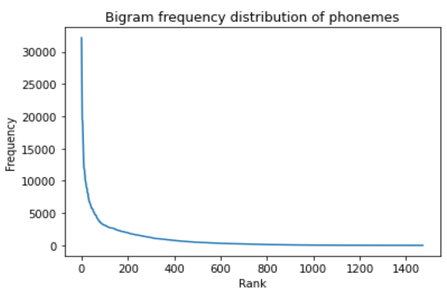
Methods

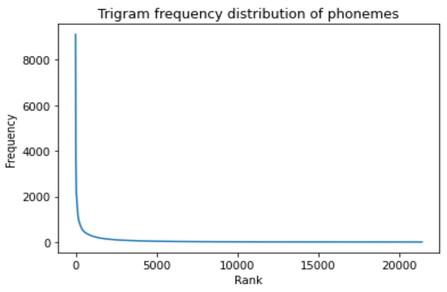
Syllables

Syllable and phonemes: Frequency distributions (Zipf law)



- Not all syllables have = frequency of use

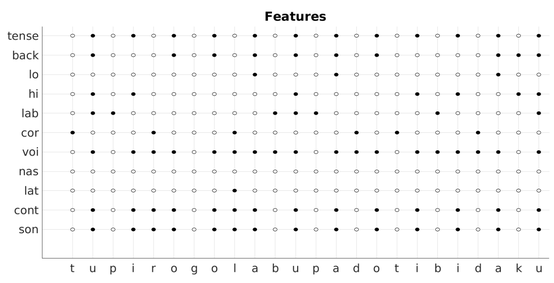




- Not all phonemes are = likely to combine

Words

Phonological information: Binary feature matrix



- Phoneme sequences in a language can be described as vectors of binary features

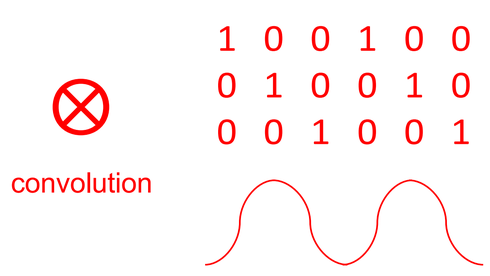
Phonotactic rules: Obligatory Countour Principle (OCP)

		MANNER		
		Sonorant (S)	Plosive (P)	Fricative (F)
PLACE	Apical (A)	n, l, r	t, d	z, ʃ, s
	Labial (L)	m	b, p	f, v
	Other (O)	h	k, g	ç

- Individual phonological features combine to form phono-articulatory classes
- Obligatory contour principle (OCP):
  - Phonological classes are less likely to be repeated consecutively within words

Lexicons

Phonological regularities: Rhythmicity index (RI)



- RI = An index that quantifies the rhythmicity of phonological features at a rate of interest

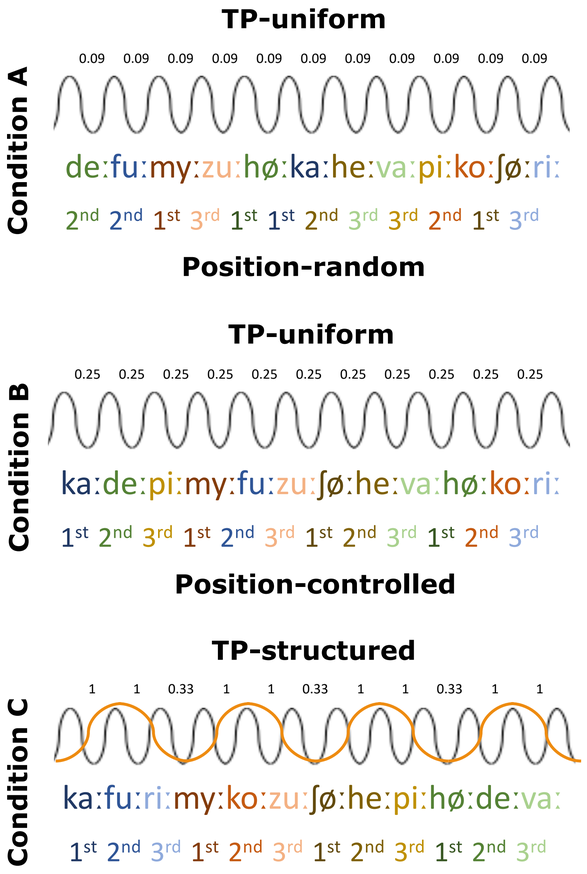
Statistical (TP) precision/stationarity: Pseudo-Random-Walk (PRW)

	0	1	2	3	4	5	6	7	8	9	10	11
0	0	1	0	0	0	0	0	0	0	0	0	0
1	0	0	1	0	0	0	0	0	0	0	0	0
2	0	0	0	0.3	0	0	0.3	0	0	0.3	0	0
3	0	0	0	0	1	0	0	0	0	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0
5	0.3	0	0	0	0	0	0.3	0	0	0.3	0	0
6	0	0	0	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	0	0	0	1	0	0	0
8	0.3	0	0	0.3	0	0	0	0	0	0.3	0	0
9	0	0	0	0	0	0	0	0	0	0	1	0
10	0	0	0	0	0	0	0	0	0	0	0	1
11	0.3	0	0	0.3	0	0	0.3	0	0	0	0	0

- Store syllable transitions in a memory matrix
- Ensure TP-stationarity throughout sequence
- Low TP variance → high precision (good!)
- High TP variance → boundaries != salience
- TP-non-stationary → spurious asymmetries

Streams

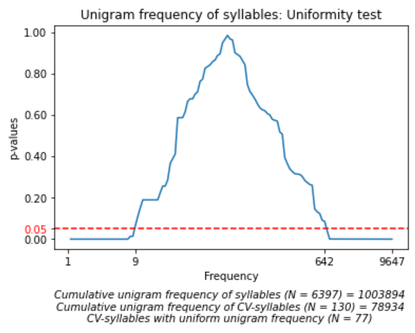
Experimental conditions: Pseudo-randomizations

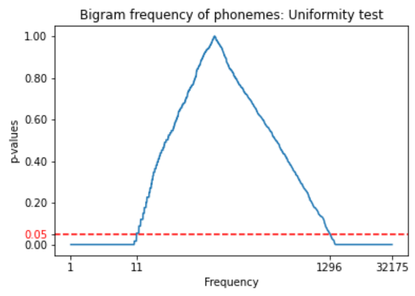


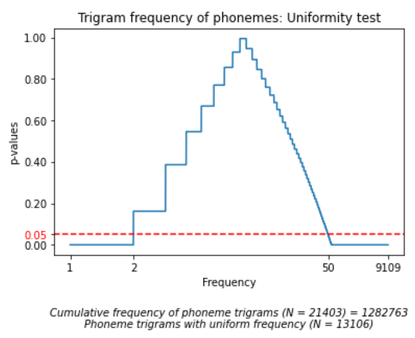
- Condition A → position-random baseline
- Condition B → position-controlled baseline
- Condition C → structured stream (learning!)

Results

Frequency control: Unigram syllable + bi/trigram phoneme







- P-values of z-frequencies distribute normally
- Syllables and phoneme combinations at the tails (too frequent or too rare) are removed

Phonological control: OCP and feature repetitiveness

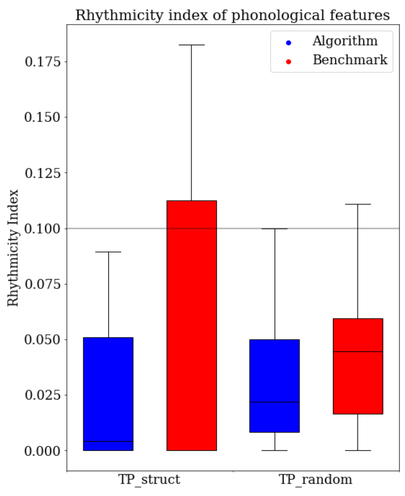
	Features	tupirogolabupadotibidaku			
consonant	*son*	0, 0, 1	0, 1, 0	0, 0, 0	0, 0, 0
	cont	0, 0, 1	0, 1, 0	0, 0, 0	0, 0, 0
	lat	0, 0, 0	0, 1, 0	0, 0, 0	0, 0, 0
	nas	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0
	voi	0, 0, 1	1, 1, 1	0, 1, 0	1, 1, 0
	cor	1, 0, 1	0, 1, 0	0, 1, 1	0, 1, 0
	lab	0, 1, 0	0, 0, 1	1, 0, 0	1, 0, 0
	hi	0, 0, 0	1, 0, 0	0, 0, 0	0, 0, 1
	back	0, 0, 0	1, 0, 0	0, 0, 0	0, 0, 1
vowel	*lab*	1, 0, 0	0, 0, 1	0, 0, 0	0, 0, 1
	hi	1, 1, 0	0, 0, 1	0, 0, 1	1, 0, 1
	lo	0, 0, 0	0, 1, 0	1, 0, 0	0, 1, 0
	back	1, 0, 1	1, 1, 1	1, 1, 0	0, 1, 1
	tense	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
Classes	*place*	A, L, A	O, A, L	L, A, A	L, A, O
	manner	P, P, S	P, S, P	P, P, P	P, P, P

- Benchmark → high feature repetitiveness

	Features	kafurimükozuʃöhepihödeva			
consonant	*son*	0, 0, 1	1, 0, 0	0, 1, 0	1, 0, 0
	cont	0, 1, 1	0, 0, 1	1, 1, 0	1, 0, 1
	lat	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0
	nas	0, 0, 0	1, 0, 0	0, 0, 0	0, 0, 0
	voi	0, 0, 1	1, 0, 1	0, 0, 0	0, 1, 1
	cor	0, 0, 1	0, 0, 1	1, 0, 0	0, 1, 0
	lab	0, 1, 0	1, 0, 0	0, 0, 1	0, 0, 1
	hi	1, 0, 0	0, 1, 0	0, 0, 0	0, 0, 0
	back	1, 0, 0	0, 1, 0	0, 0, 0	0, 0, 0
vowel	*lab*	0, 1, 0	1, 0, 1	0, 0, 0	0, 0, 0
	hi	0, 1, 1	1, 0, 1	0, 0, 1	0, 0, 0
	lo	1, 0, 0	0, 0, 0	0, 0, 0	0, 0, 1
	back	1, 1, 0	0, 1, 1	0, 0, 0	0, 0, 1
	tense	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
Classes	*place*	O, L, A	L, O, A	A, O, L	O, A, L
	manner	P, F, S	S, P, F	F, S, P	S, P, F

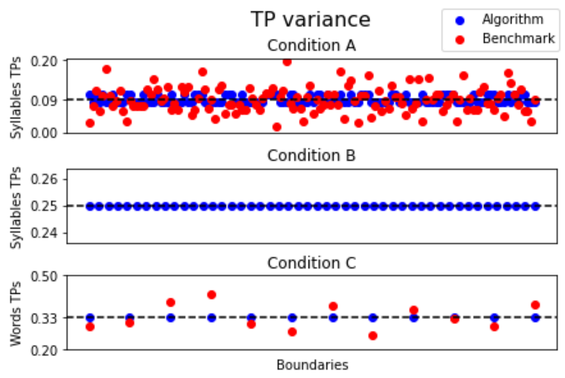
- Algorithm → low feature repetitiveness

Phonological control: RI of phonological features



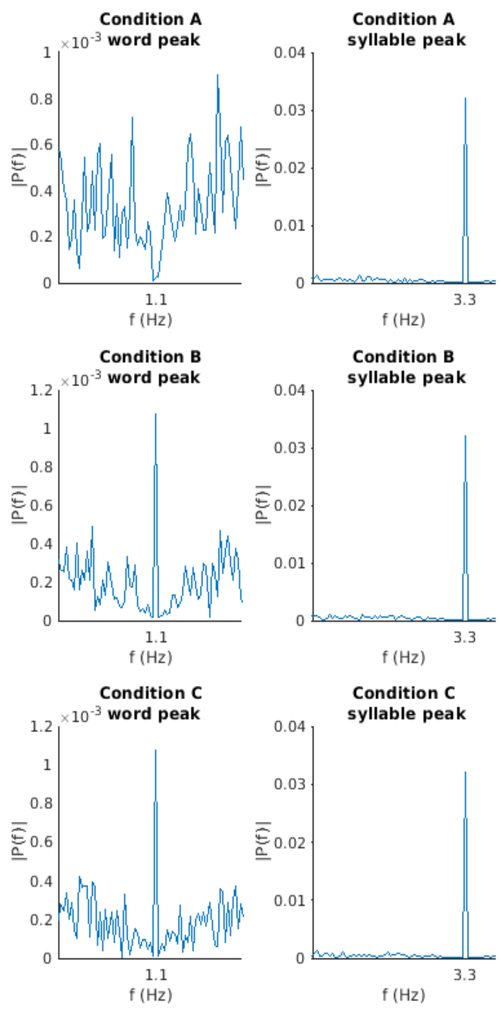
- Benchmark → high RI on some features
- Algorithm → low RI (< 0.1) on all features

Statistical (TP) control: Pseudo-Random-Walk (PRW)



- Benchmark → high TP variance (bad!)
- Algorithm → zero TP variance (good!)

Acoustic control: Spectral analyses



- A vs C → Different word peak (1.1 Hz)
- B vs C → Same word peak (1.1 Hz)
- B (but not A) is a good baseline for C

Discussion

Summary

- Step 1: Select syllables and phoneme combinations with uniform frequency of use
- Step 2: Generate artificial words that obey phonotactic constraints (OCP: place and manner)
- Step 3: Generate lexicons that minimize the RI of phonological features at the word rate
- Step 4: Generate streams with high TP precision and eliminate spectral differences

Future directions

- More versatility: Beyond German; Beyond trisyllabic words; Lexicons of variable size
- Use RI in NFT paradigms to test cortical tracking of individual phonological features
- Use PRW for high precision and stationarity of TPs in all types of SL experiments
- Find latent stimulus features (e.g., autoencoder network) that are salient for the brain

References

[1] Saffran et al. (1996). *Science.* 274. [2] Buiatti et al. (2009). *NeuroImage.* [3] Batterink et al. (2017). *Cortex*. [4] Ordin et al. (2020). *Eur. J. Neurosci.* [5] Henin et al. (2021). *SciAdv*. [6] Pinto et al. (2022). *NOL*. [7] Kiai & Melloni (2021). *bioRxiv*. [8] Chen et al. (2020). *Neuropsychologia*.