Is syntax optimized for periodic neurobiological sampling? Evidence from 21 languages

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Introduction

- The goal of language comprehension: link words/morphemes in a sentence.
- However, working memory constraints and the period of neuronal time windows may set an upper limit for language comprehension:

o Auditory short-term memory is limited to 2-3 seconds [1].
o A proposed window of 2.4 seconds, including ~6 words when assuming a rate of 150 words per minute [2-3].
o Cycles of low-frequency neural activity serve the formation of multi-word chunks [4-5]:
  – A 2.7-s time window for optimal multi-word chunk duration [6].
  – Eye-movements during naturalistic reading are synchronized with the delta-band oscillatory activity (~1 Hz) for multi-word chunks [7].
  – Self-paced reading time data reveal periodic patterns at ~2 Hz [8].

- If the wavelength of periodic brain activity indeed sets a neuronal timing constraint on multi-word chunking, this should be reflected in the languages of the world: Multi-word chunks should exhibit temporal regularity.
- This limit should be observable as periodicity and a tendency for isochrony across different languages.

Methods

- UD corpus of 21 languages (>10,000 sentences, [9])
- Annotate with a chunking model [8]
- Timing: speech synthesis (Google WaveNet)

Periodicity = equispacing of chunks

- Assessing equispacing: consider distribution of inter-chunk intervals (ICIs)
- If distribution of little variance and peaky, chunks are more periodic.

o Comparison: dithering of chunk offsets (1,000×)
o Coefficient of variation (CV): variability of chunk spacing
  H1: ICIs less variable than random

$$CV = \frac{\sigma}{\mu}$$

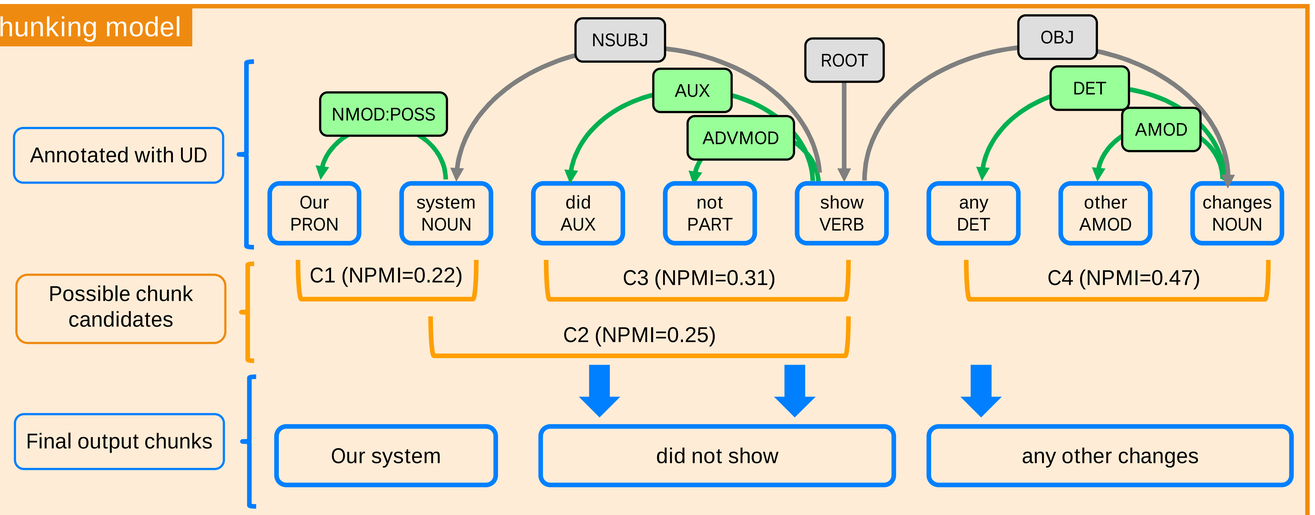
o Fano factor: variability of chunk rate
  H1: Chunk rate less variable than expected by chance

$$F = \frac{var\ (Rc)}{mean\ (Rc)} \quad Rc = chunk\ rate$$

Typological variability

- Post-hoc correlational analyses are performed between ICI matrics and word-order predictability from [10].

Chunking model

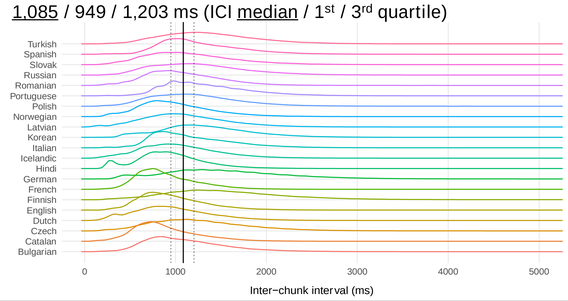


NPMI: normalized pointwise mutual information

Results

1 Inter-chunk intervals

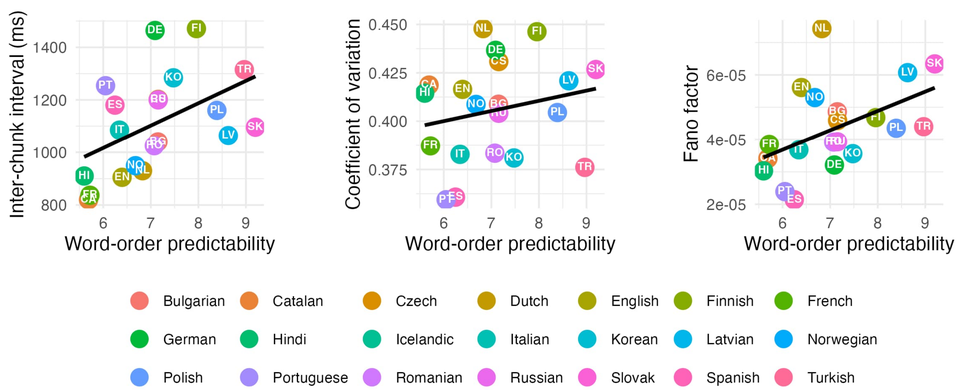
1,085 / 949 / 1,203 ms (ICI median / 1st / 3rd quartile)



2 CV & Fano factor

Language	Sentences (n)	ICI (ms)	Coefficient of variation		Fano factor	
			Observed	Cutoff	Observed	Cutoff
Turkish	15,456	1,315	0.38	0.46	4.40E+09	4.53E+08
Spanish	16,482	1,180	0.36	0.43	2.14E+08	2.16E+09
Slovak	8,257	1,096	0.43	0.49	6.34E+09	6.57E+09
Russian	77,748	1,200	0.40	0.46	3.93E+09	4.04E+09
Romanian	25,193	1,025	0.38	0.44	3.92E+09	3.97E+09
Portuguese	10,705	1,254	0.36	0.43	2.39E+09	2.42E+09
Polish	20,648	1,160	0.40	0.46	4.35E+09	4.46E+08
Norwegian	17,527	949	0.41	0.47	5.30E+09	5.42E+09
Latvian	14,573	1,064	0.42	0.48	6.07E+09	6.15E+09
Korean	25,550	1,284	0.38	0.45	3.56E+09	3.63E+09
Italian	13,123	1,085	0.38	0.45	3.68E+09	3.77E+09
Icelandic	42,112	1,000	0.41	0.46	4.74E+09	4.80E+09
Hindi	16,572	910	0.41	0.46	3.03E+09	3.07E+09
German	173,199	1,464	0.44	0.49	3.21E+09	3.26E+09
French	15,272	837	0.39	0.45	3.85E+09	3.91E+09
Finnish	12,917	1,471	0.45	0.50	4.68E+09	4.80E+09
English	12,190	905	0.42	0.48	5.61E+09	5.79E+09
Dutch	11,889	930	0.45	0.50	7.43E+09	7.56E+09
Czech	75,634	1,202	0.43	0.48	4.59E+08	4.75E+09
Catalan	15,348	820	0.42	0.46	3.41E+09	3.41E+09
Bulgarian	10,120	1,040	0.41	0.47	4.86E+09	5.00E+09

3 Typology: flexible word order = more periodicity



Discussion

- Results 1: We found non-uniform distributions of ICIs across languages and the average of median ICIs across languages is 1.1 seconds.
  ➢ Chunks within and across languages are periodic, at least to some extent.
- Results 2: Decreased ICI variances and Fano factors relative to surrogate data generated from 1,000 permutations of random chunks.
  ➢ Chunk spacing is less variable than expected for a fully random, non-isochronous chunk rate, and also less variable than expected when assuming randomness for each language.
- Results 3: Positive correlations between word-order predictability and ICI median ($r(19) = .48$, $p = .03$) and Fano factor ($r(19) = .49$, $p = .03$), but not coefficient of variation ($r(19) = .21$, $p = .36$); these did not withstand FDR correction.
  ➢ There may be trade-off between periodicity and speech content.

- Memory constraints might limit the distance of dependency between words and bound morphemes and these are reflected in the wavelength of periodic neural activity (a.k.a. *neural oscillations*) across different languages.
- Languages with more flexible word orders might have shorter chunks and more periodicity, suggesting that the ontogenetic neural constraint can be bent by cultural differences, within limits.

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