Efficient phonological clustering in the mental lexicon

Kyle Mahowald, Isabelle Dautriche, Edward Gibson,
Anne Christophe, Steven T. Piantadosi

What we know about the lexicon

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kakis
gato
pusa
kottur
chat
Katze

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- The relationship between word forms and their meanings is **arbitrary**.

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- The set of word forms may be designed for:
  - **communicative efficiency**
    - Efficient codes in the presence of noise have maximum distance between codewords
  - **ease of processing and learnability**
    - Easier to remember and produce things that are similar to things you already know

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Lexical design: Clumpish

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fep

‘COLD’

Lexical design: Clumpish

fep
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feb
‘HOT’

Lexical design: Clumpish

fep ‘COLD’  feb ‘HOT’

- Allows you to re-use sounds you already know which makes it easy to learn and process, but you might get confused.

Lexical design: Sparsese

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- More optimal from efficient coding perspective
- But you have to learn and store a new set of sounds.

Overview

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- Two approaches:
  - Large-scale analysis of lexicons
  - Comparison of natural languages to plausible “null” lexicons

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- Can a pressure for dispersion /clumpiness be found in the frequency patterns of word use? (see Frauenfelder et al., 1993)
  - **Dispersion**: the most frequent words should be more unique phonologically
  - **Clumpiness**: the most frequent words should share more sequences

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- For each word type, calculate:
  - number of **neighbors** (car/cat and cat/cats)
  - token **frequency**
  - **orthographic probability** as a proxy for phonotactic probability (using a 3-gram model)

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- Frequent words have fewer neighbors and lower probability

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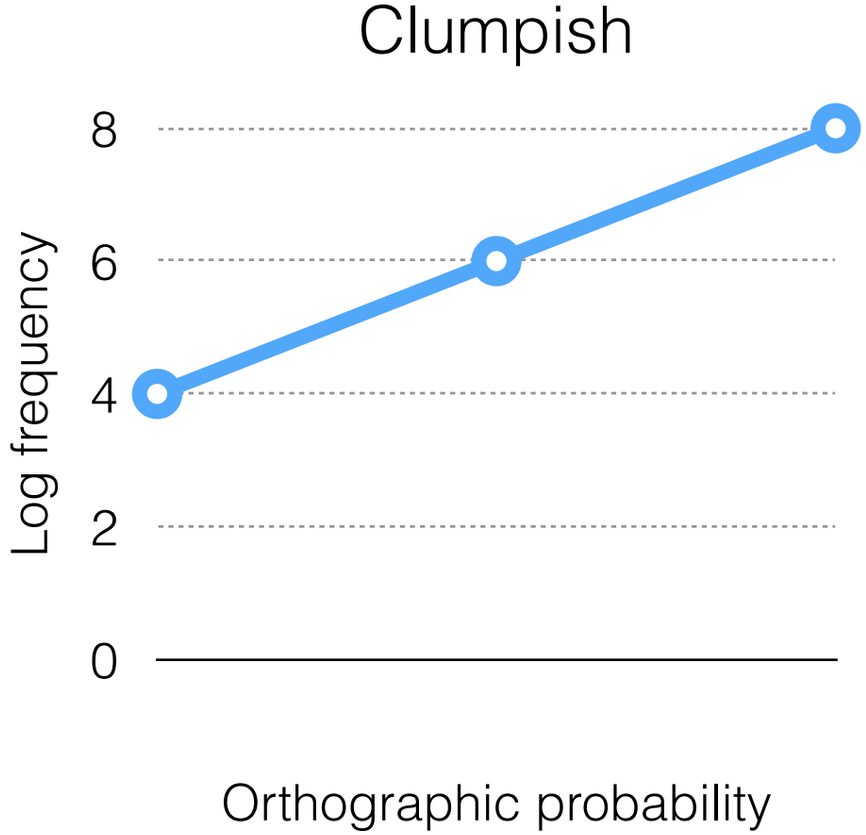

- Frequent words have fewer neighbors and lower probability

Possible results

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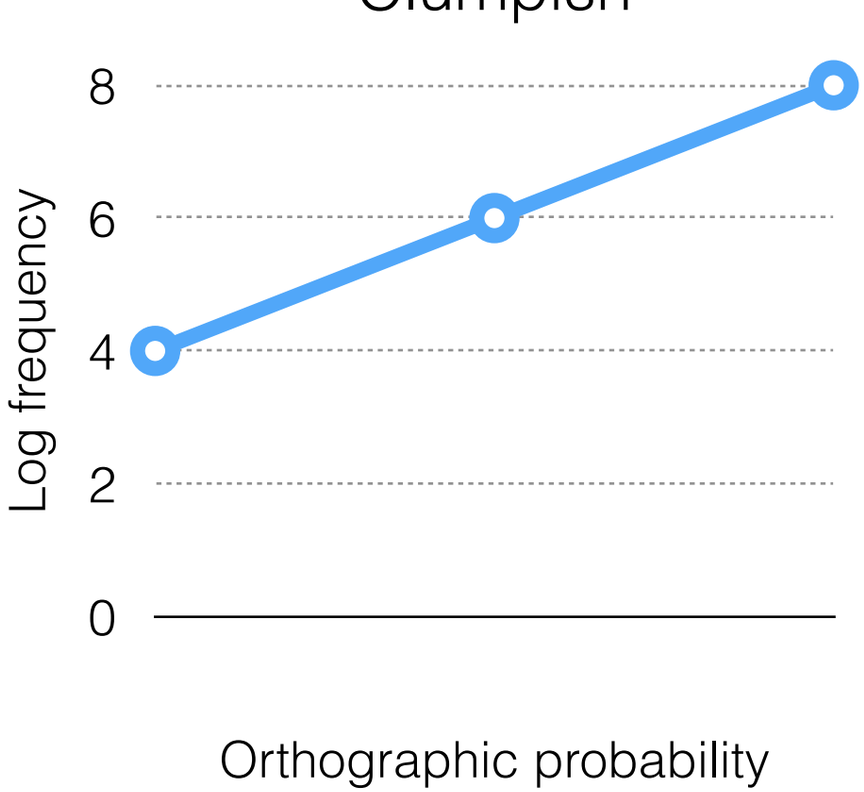
Clumpish



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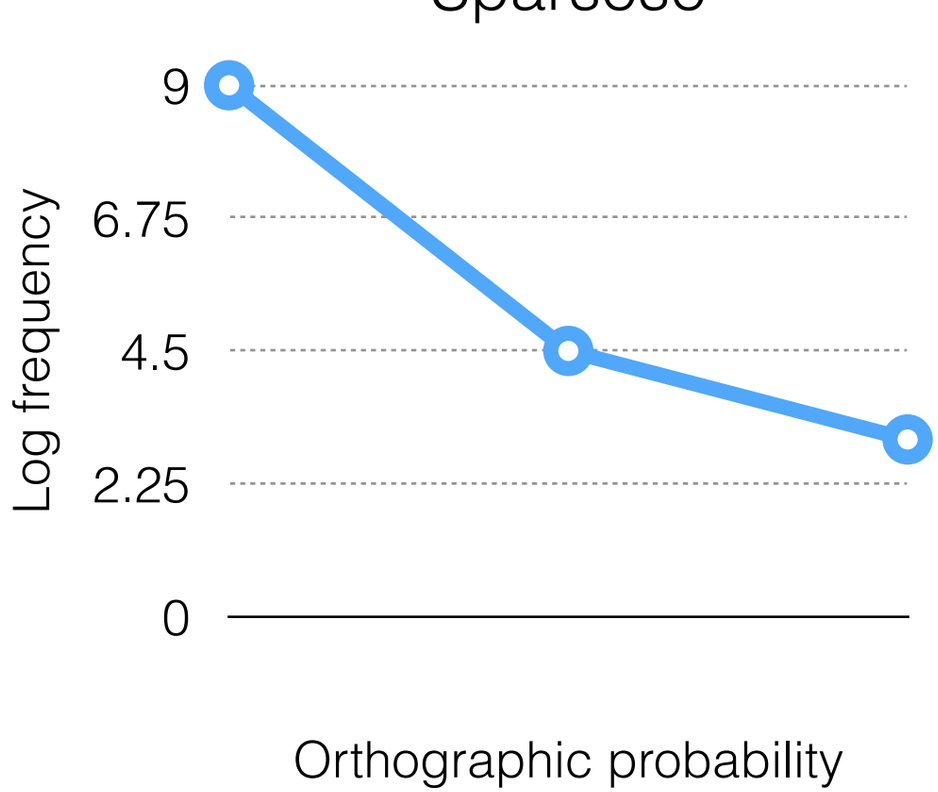
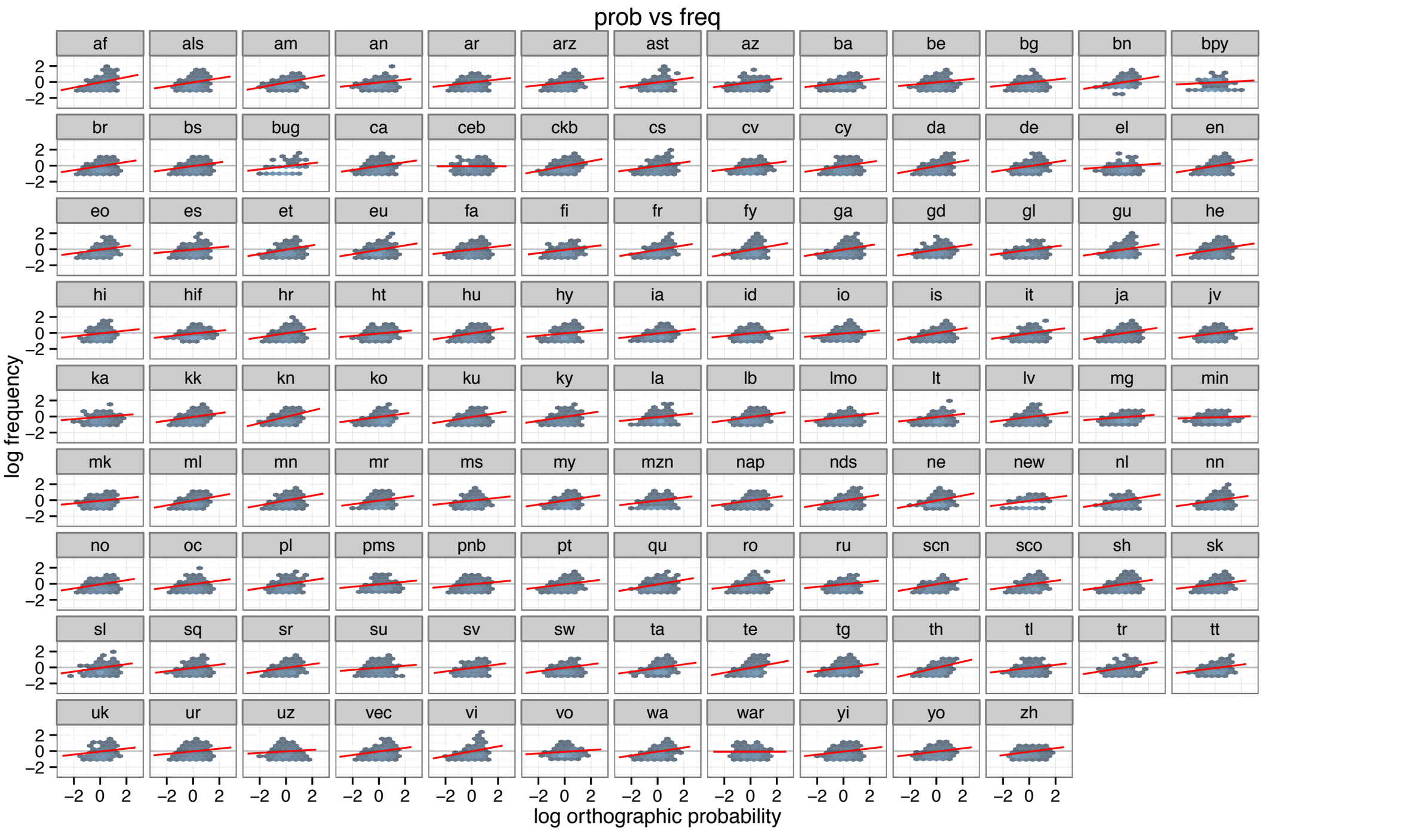
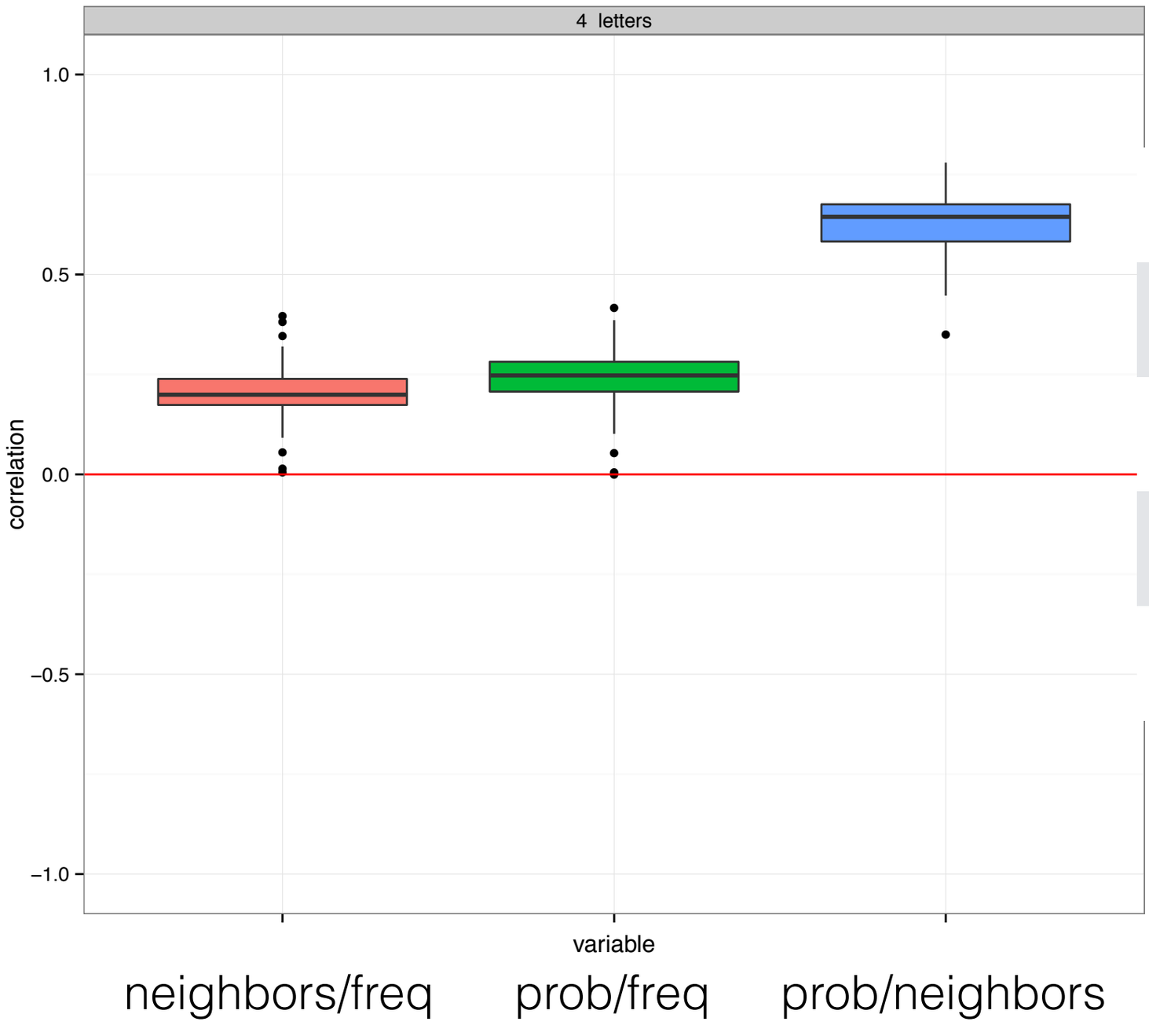
Sparsese



Wikipedia (4-letter words)



Wikipedia results



	mean	pos.	sig
neighbors/ freq	0.21	0.97	0.96
prob/freq	0.24	0.97	0.99
prob/ neighbors	0.63	1.00	1.00

(other lengths similar)

Results summary

- Across 115 languages, we found:
  - an obvious correlation between orthographic probability and number of neighbors (more common words have more neighbors)
  - correlations between number of neighbors and frequency
- **This suggests a pressure for clumpiness that becomes stronger with use.**
- Possible confound: morphemes
- Yet this effect is predicted by a model of word generation: more probable strings will be generated more often and higher string probabilities give rise to more neighbors.
  - We need a proper baseline.

Simulating “null” lexicons

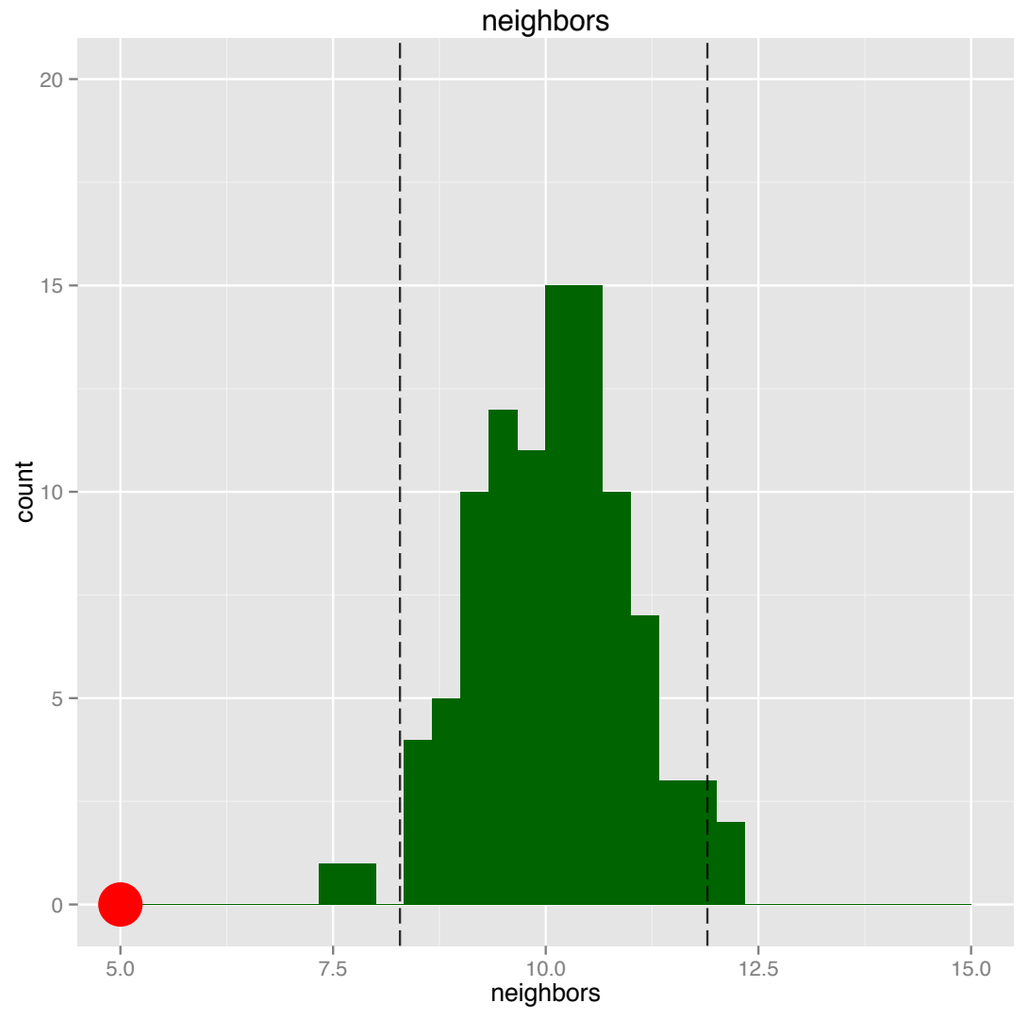
- Is the lexicon clumpier than what would be expected by chance alone?
  - How do we determine what a baseline is?
- New method
  - Generate “null” lexicons for which there is no pressure for dispersion or clumpiness, beyond phonotactics
  - Compare real lexicons to these null lexicons on a variety of lexical measures to see how they are different.

Method

- **Real lexicons (phonemic transcriptions)** are **monomorphemic** lemmas from Dutch, English, German (CELEX), French (Lexique)
  - 4000 to 6000 words, no homophones, freq > 0
- **Models of phonotactically controlled lexicons**
  - n-phone models (n=1 to n=6)
  - n-syllable models (n=1 to n=2)
  - PCFG over syllables
- All with back off and smoothing, all matched for length to the real lexicon
- Sample 30 “null” lexicons for each
- **Select the best model**
  - Each model trained on 75% of the real lexicon and evaluated on the remaining 25%
- **Best model: 5-phone model** (50% of generated words, on average, are real)
- **Measure of word form similarity:** number of minimal pairs, average Levenshtein distance (edit), network measures..

Hypothesis 1: Sparsese

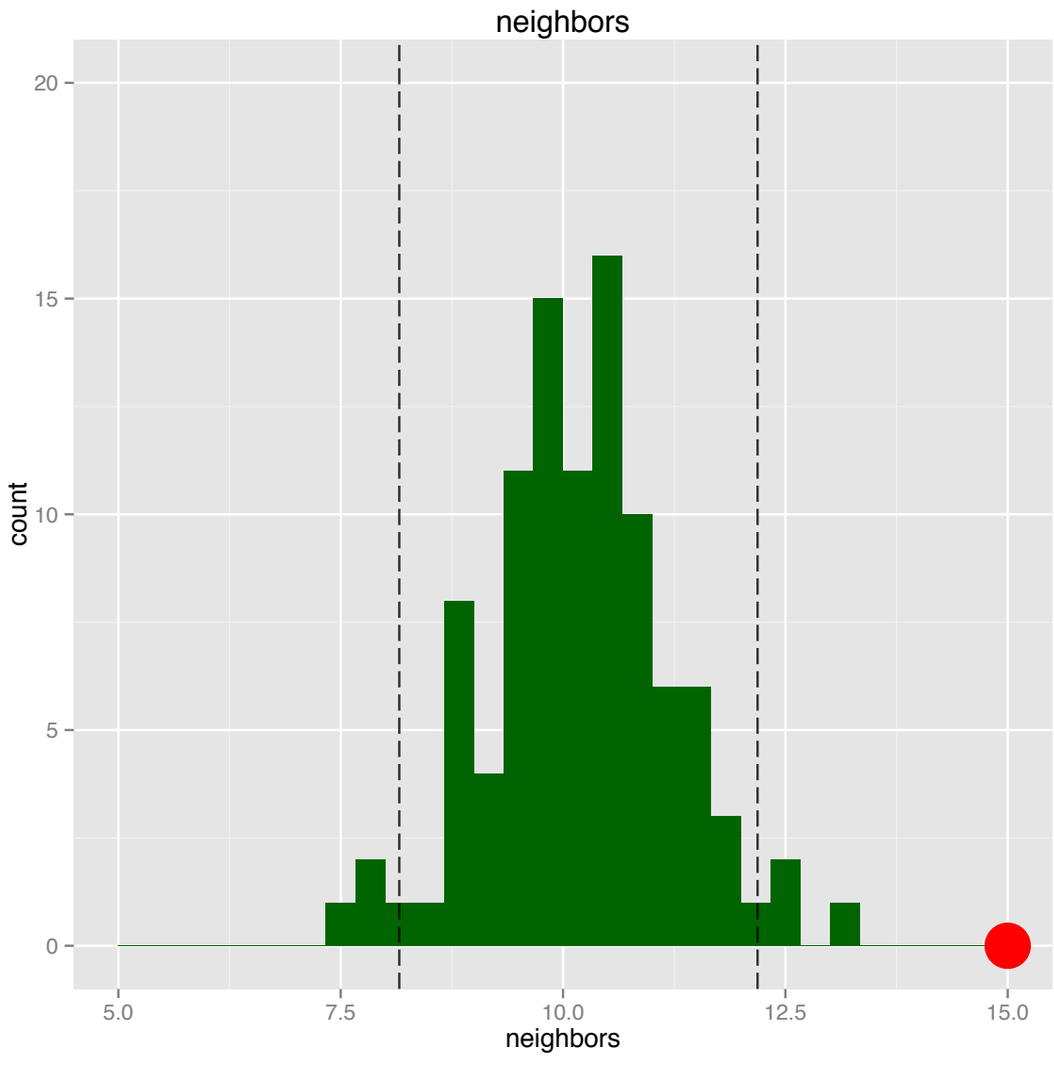
- Neighbors and minimal pairs (pig/big) are avoided in order to create a sparse code.



red dot: number of minimal pairs in the real lexicon
green histogram: the distribution of the number of minimal pairs across simulated lexicons
dotted line: 95% confidence interval

Hypothesis 2: Clumpish

- Minimal pairs and neighbors are more likely due to pressure for re-use and regularity (i.e., having *big* in the lexicon makes *pig* more likely)



red dot: number of minimal pairs in the real lexicon
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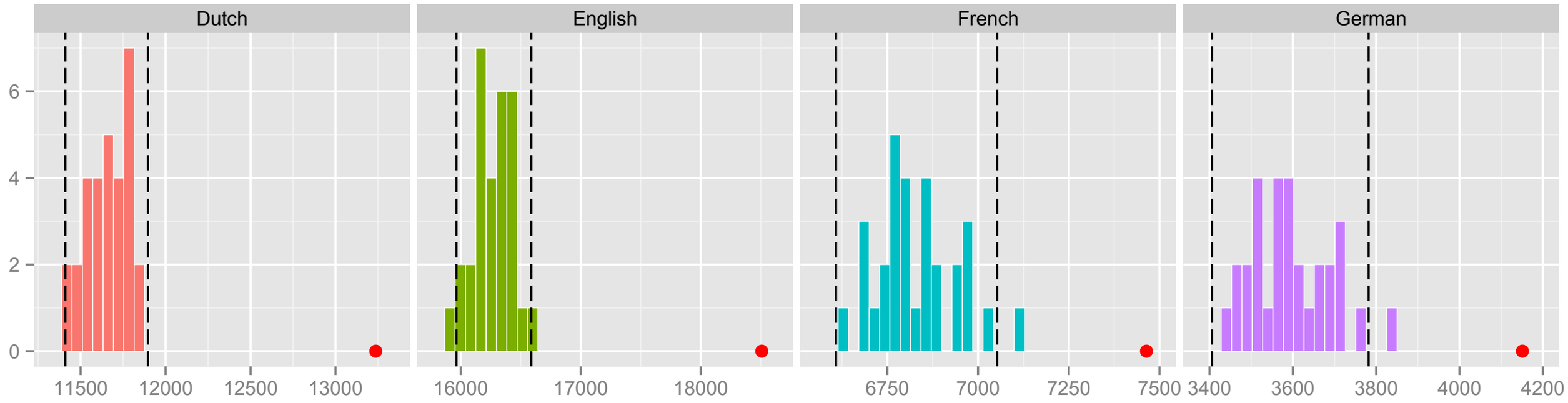
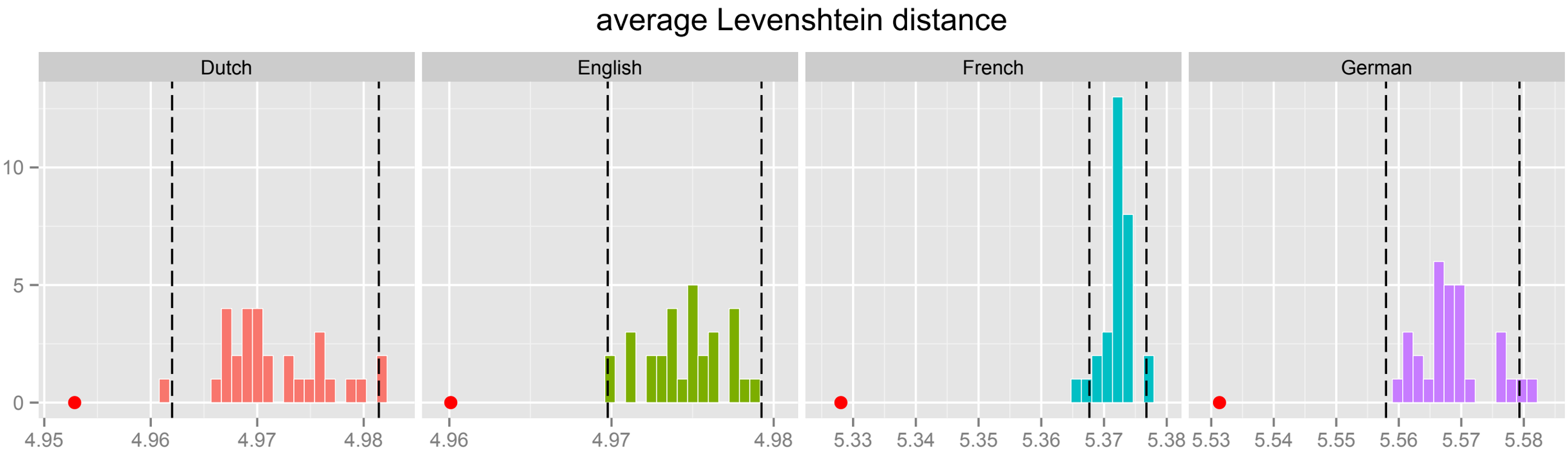
Result: number of minimal pairs



- More minimal pairs in all 4 real lexicons than expected by chance (especially true for small lengths).

Another measure: Average Levenshtein distance



- Word forms are more similar in the real lexicon.
- Additional measures (network transitivity, clustering coefficient) tend towards the same conclusion: the lexicon is clumpy.

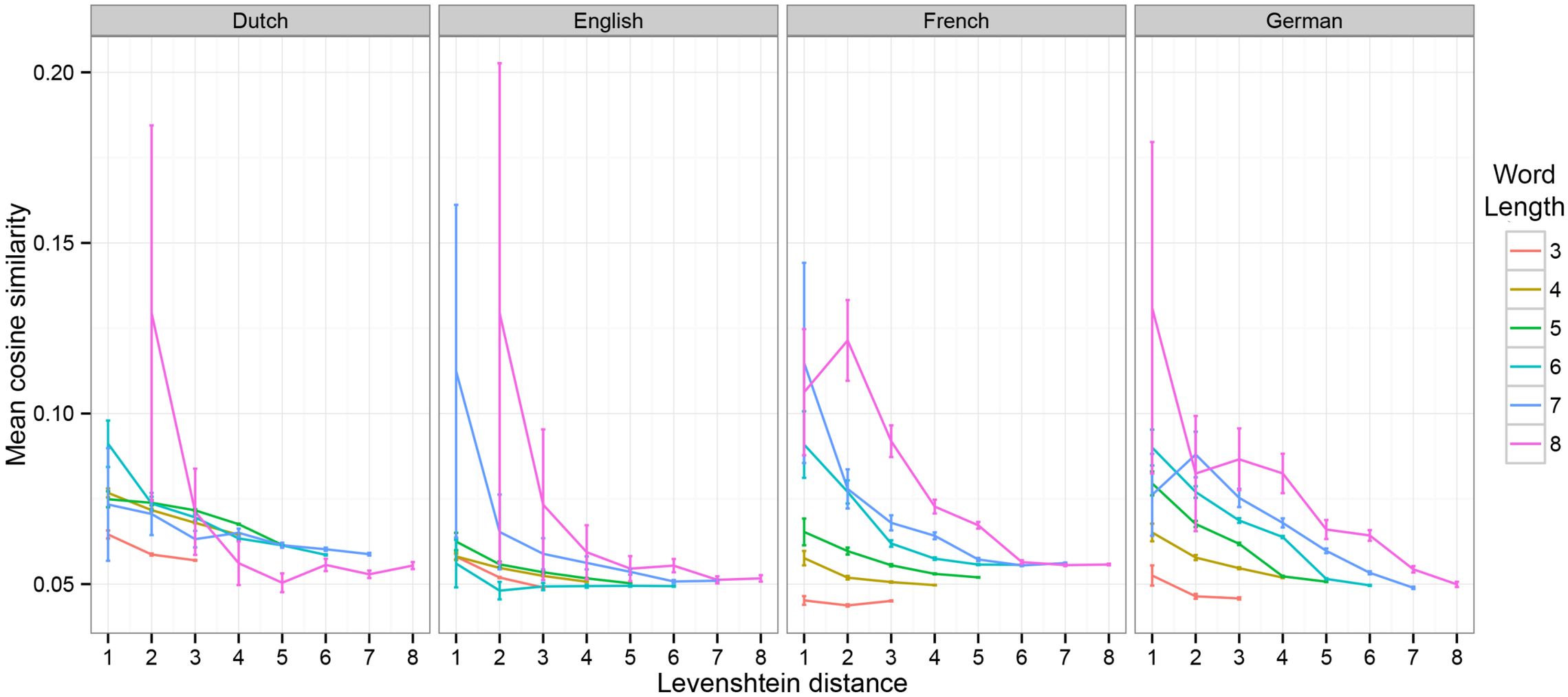
Null lexicon summary

- Most of the measures reviewed suggests that **the lexicon is clumpier than expected by chance.**
  - **Not** the result of morphological regularity since we focused on **monomorphemes**
  - Not the result of sound-to-sound transition probability controlled for by model

Possible role of semantics

- Is there a relationship between form and meaning at the large scale? (cf. Monaghan, et al. 2014)
- 4 lexicons, calculate for each word pair:
  - phonological edit distance
  - semantic similarity using co-occurrence vectors from LSA

Possible role of semantics



Even antonyms are clumpy

fep
'COLD'

feb
'HOT'

- 42 English antonym pairs (happy/sad) that are not morphologically related. Look at Levenshtein distance compared to all other words in set of 84.

- The average Levenshtein distance between a word and its antonym was 3.64 compared to 3.98 between a word and a non-antonym. Significant by mixed effect model (β=-.08, t=-4.11, $p < .001$).

Global summary

- Large-scale analysis of Wikipedia: Most frequent words share more sound sequences pointing towards **clumpiness**

- Null lexicon results: The lexicon is **clumpier** than expected by chance across most measures of word form similarity

Thanks!

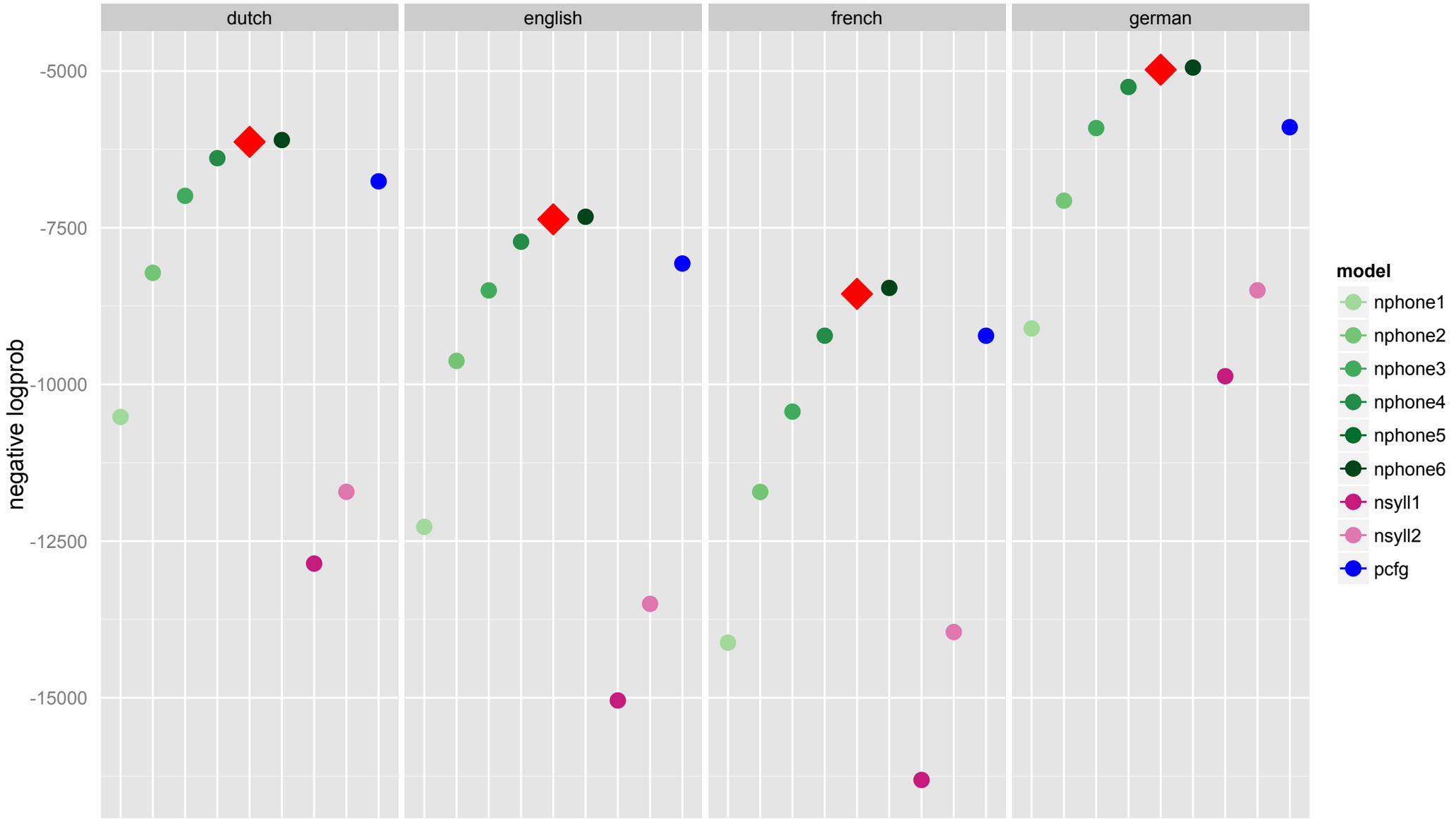



- Collaborators: Isabelle Dautriche, Ted Gibson, Anne Christophe, Steve Piantadosi

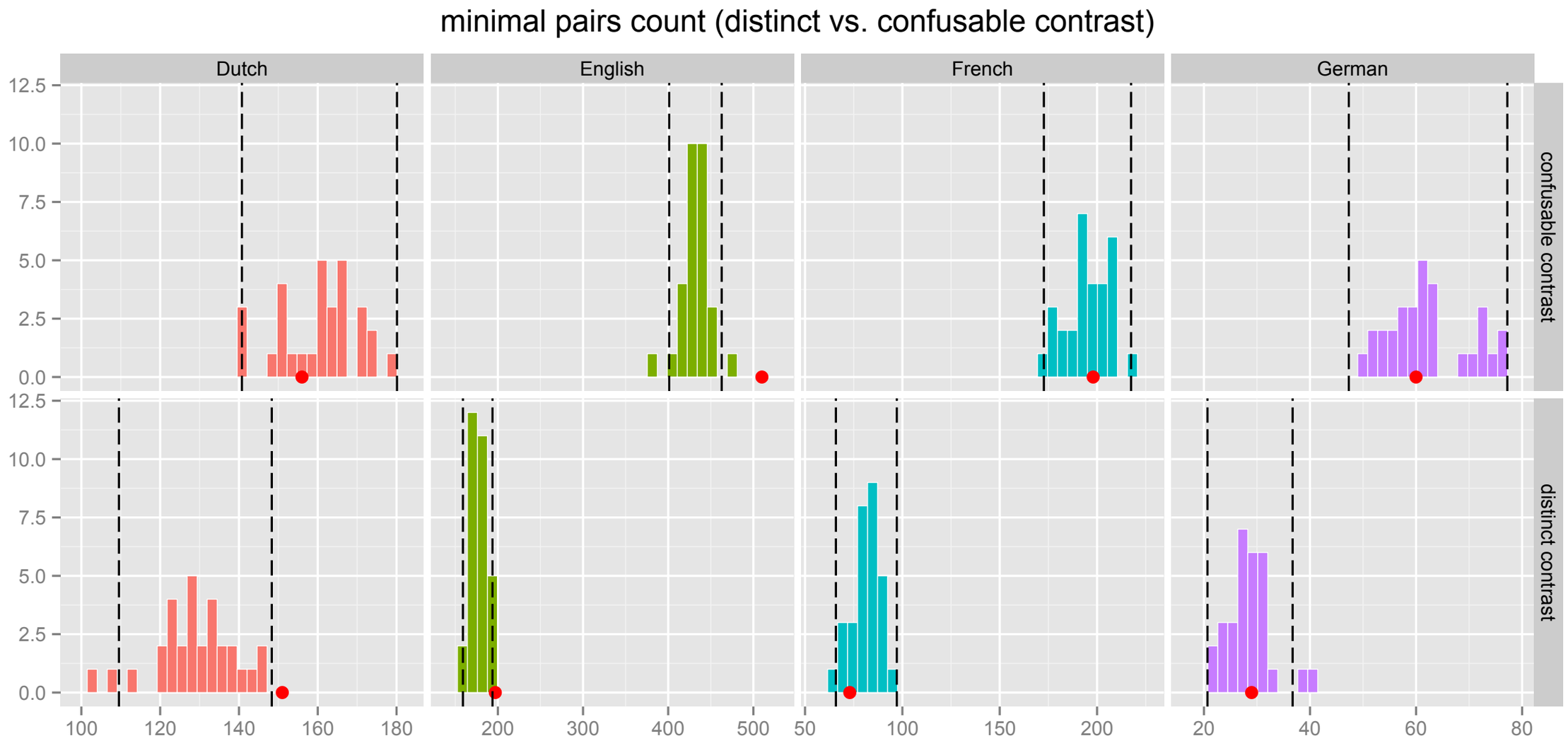
- Members of Tedlab

- Audience at AMLaP 2014

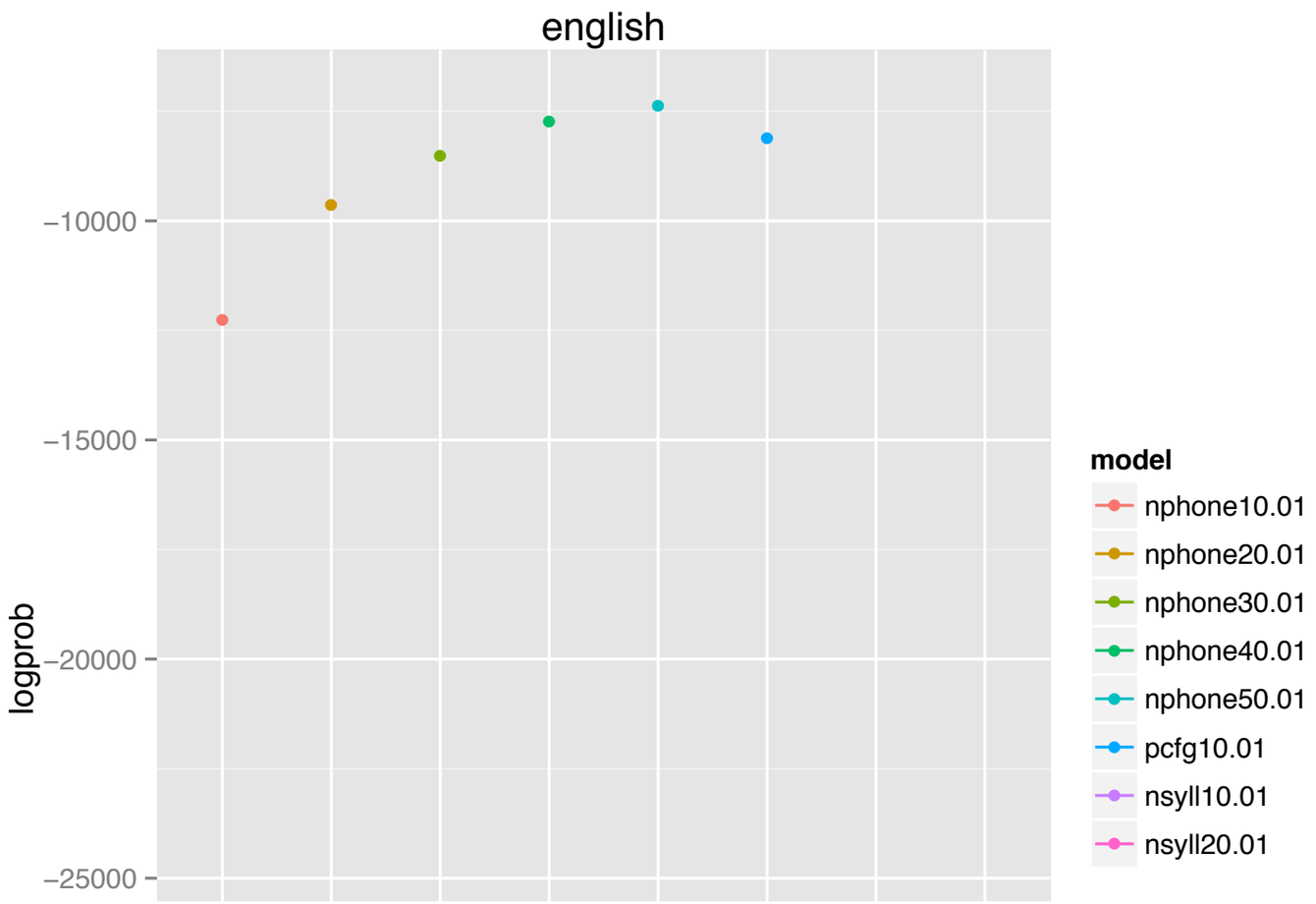
Evaluation


dutch
english
french
german
-5000
-7500
-10000
-12500
-15000
negative logprob
model
nphone1
nphone2
nphone3
nphone4
nphone5
nphone6
nsyll1
nsyll2
pcfg

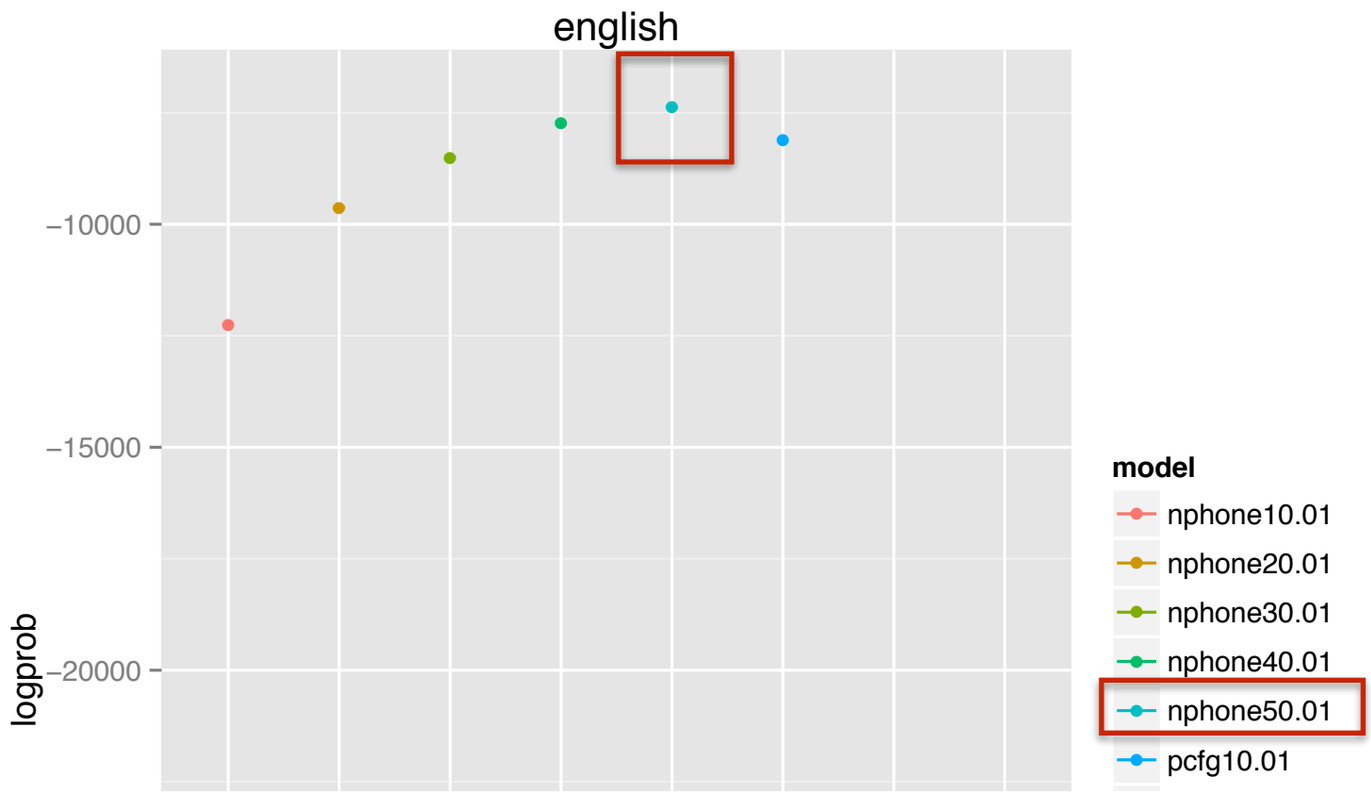
Confusable vs. non-confusable MPS



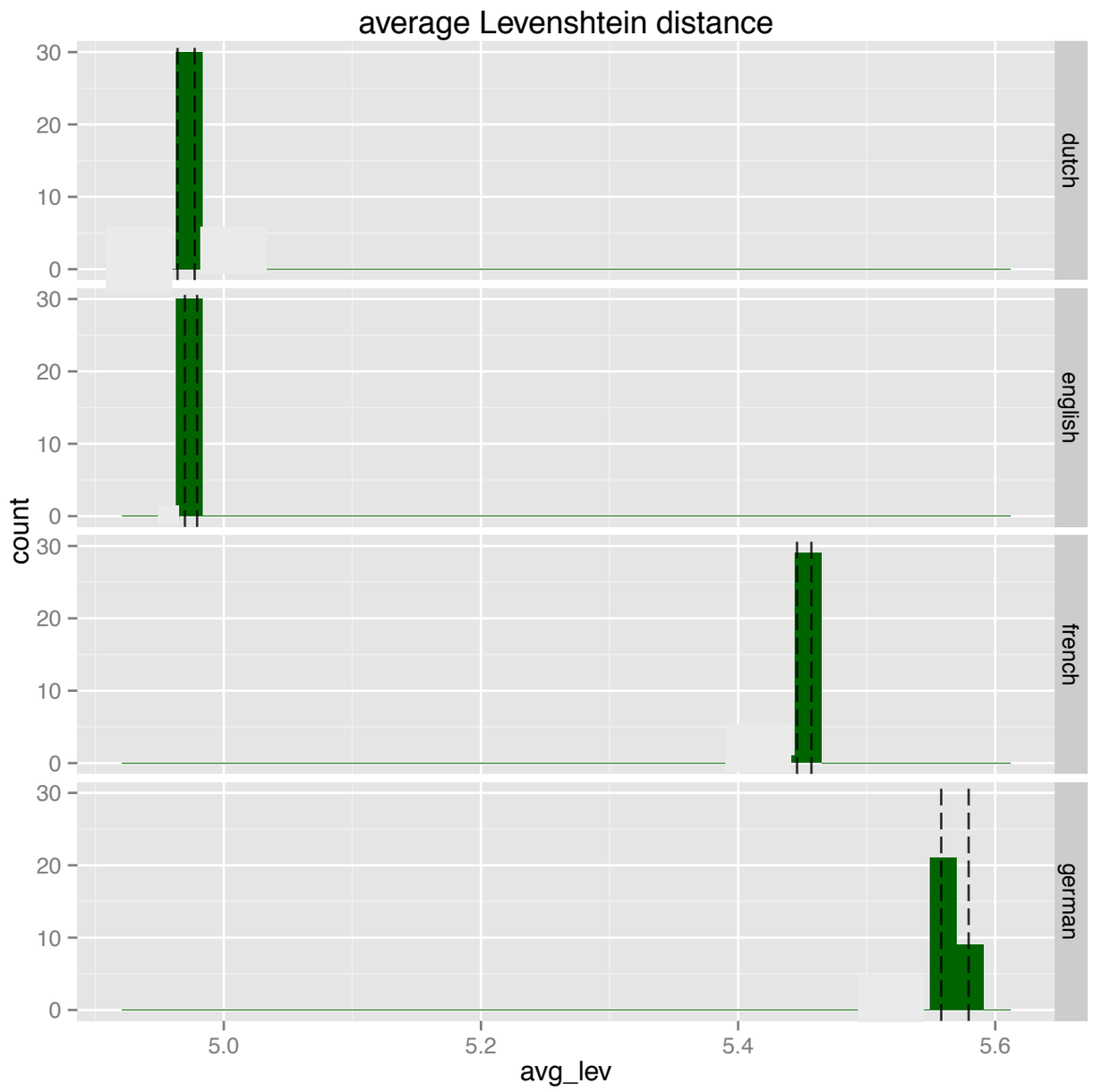
Clumpiness and semantic factors



Evaluating models (train on .75; test on .25)

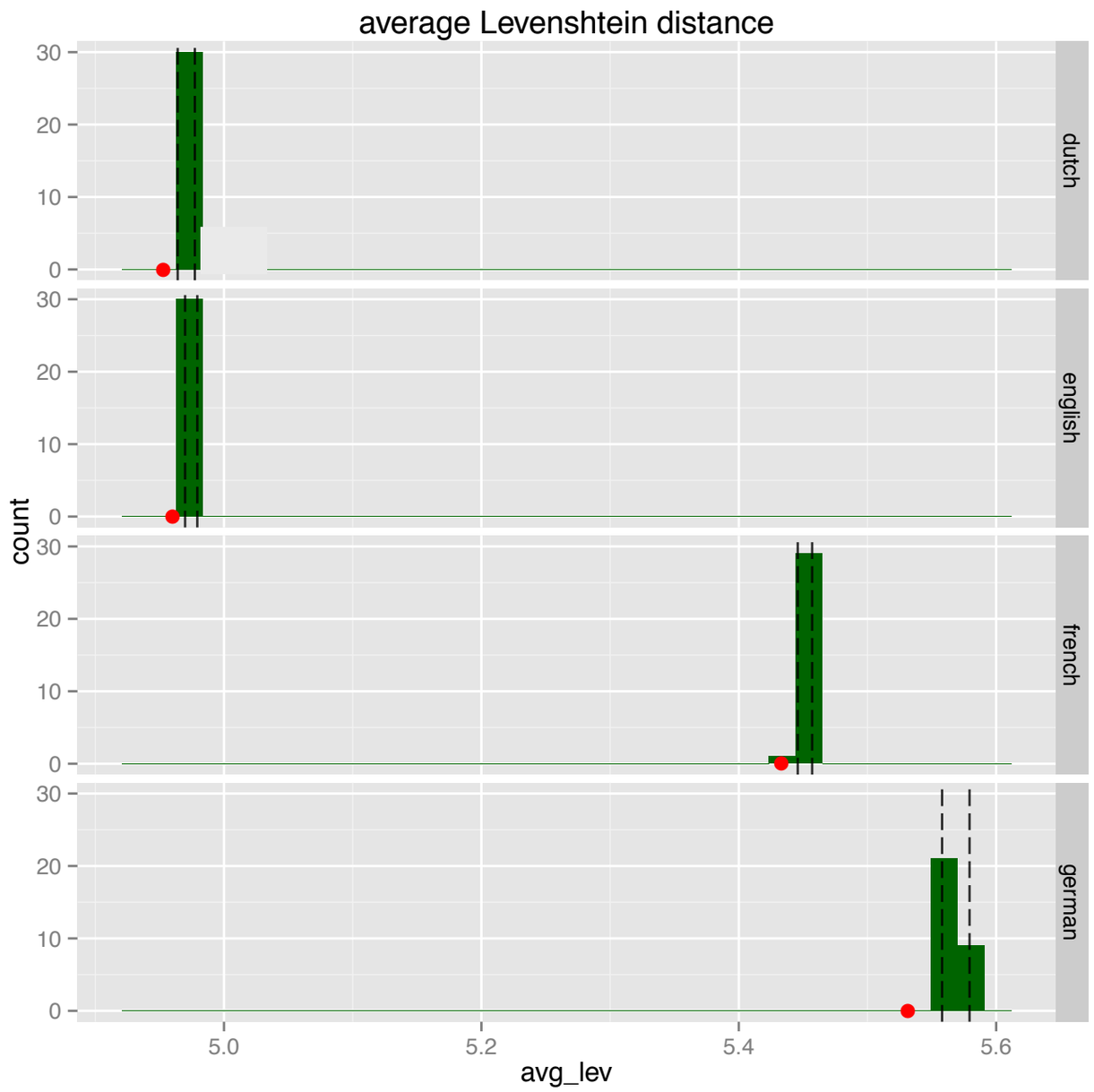


Results: Edit distance

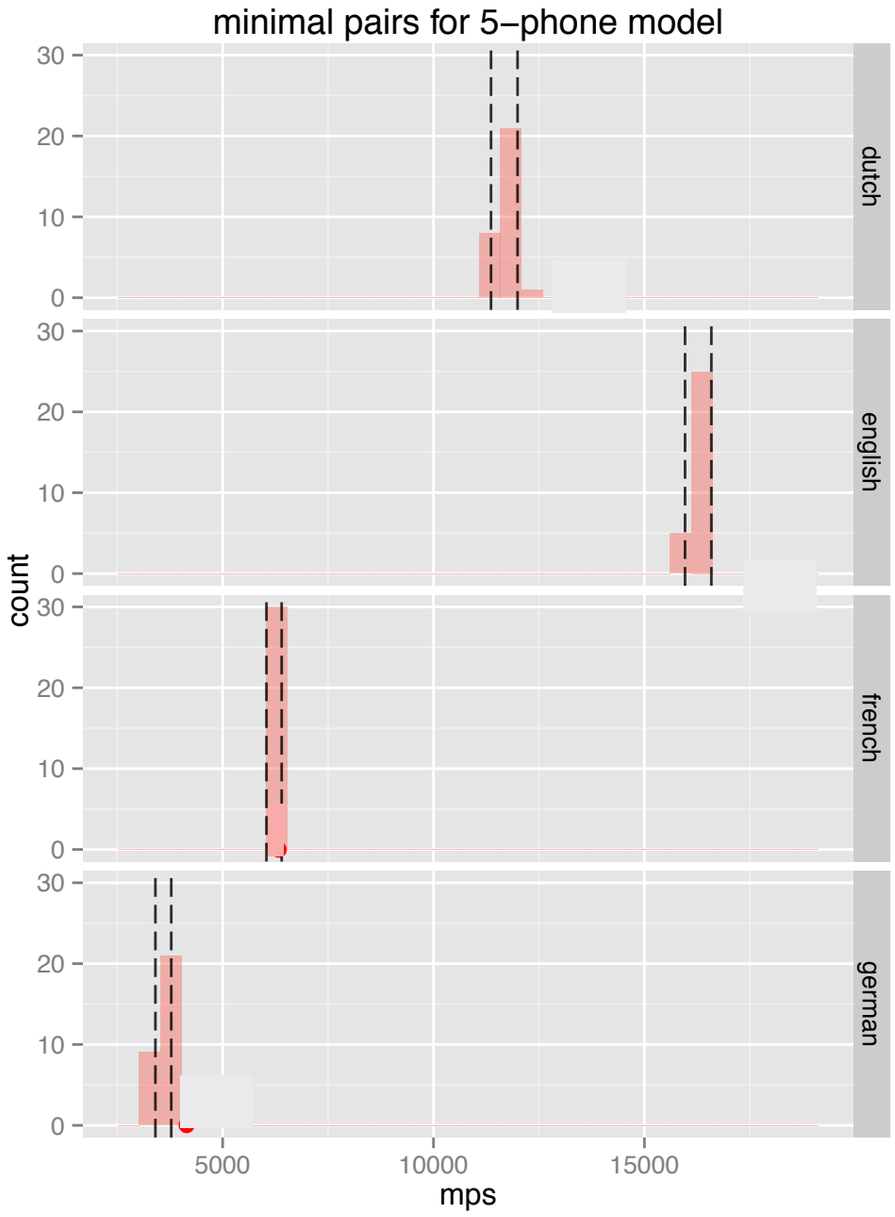


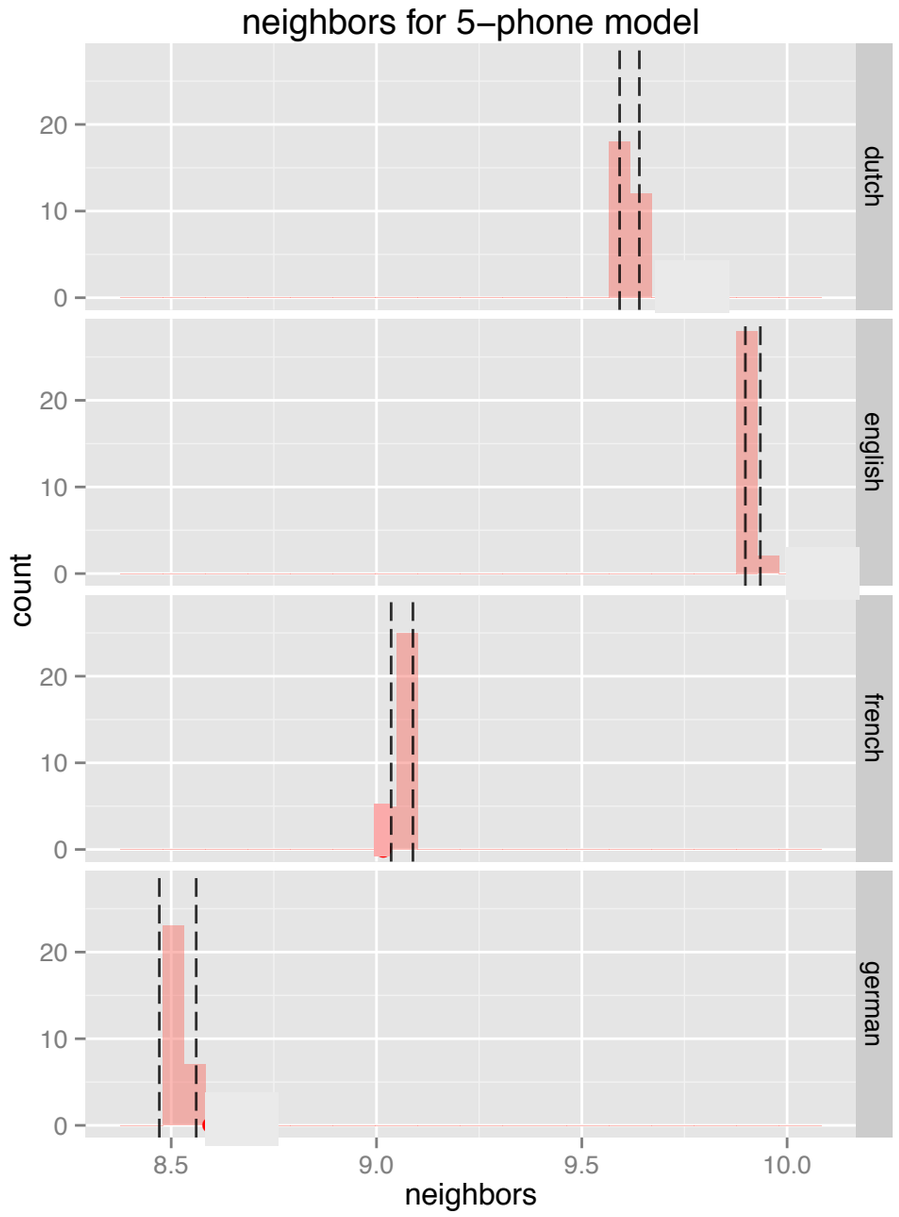
Results: Edit distance

clumpy



Results: Neighbors and minimal pairs





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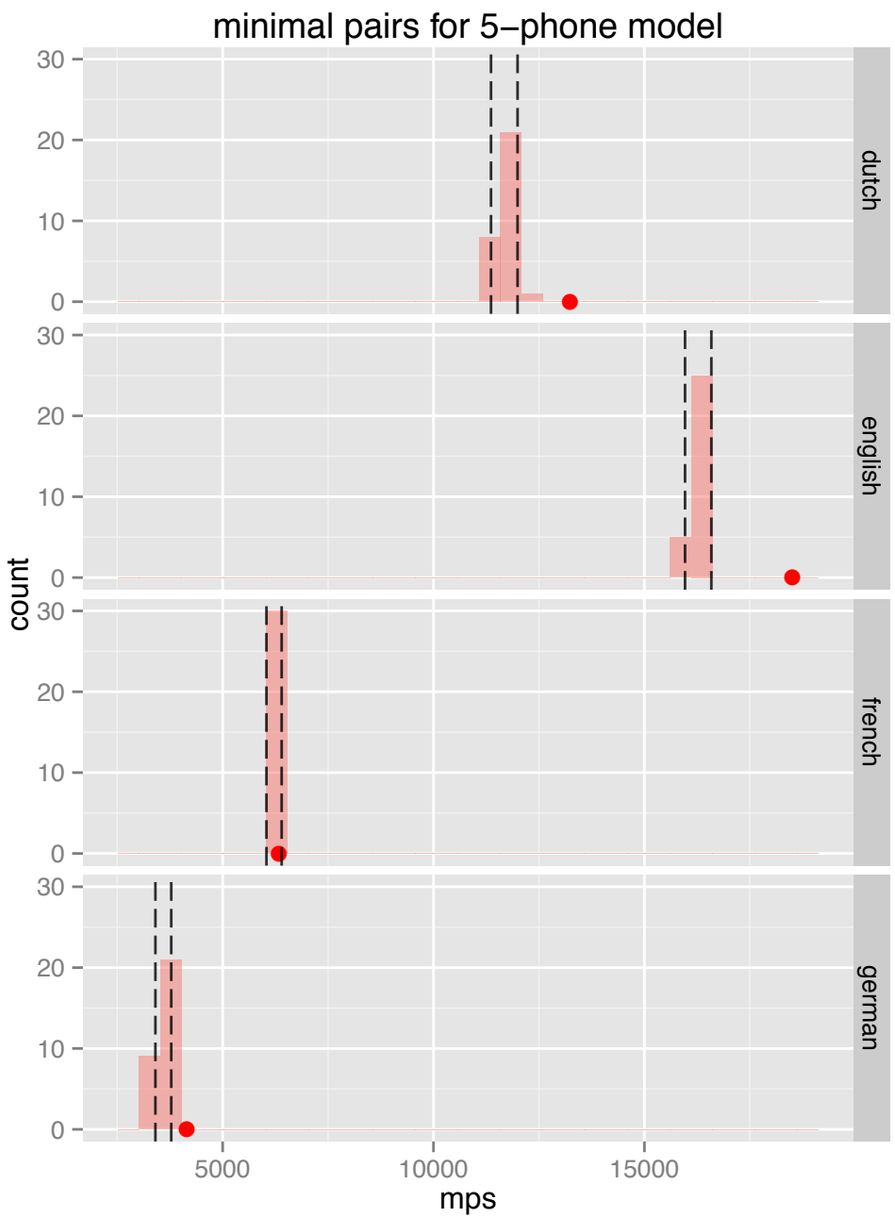
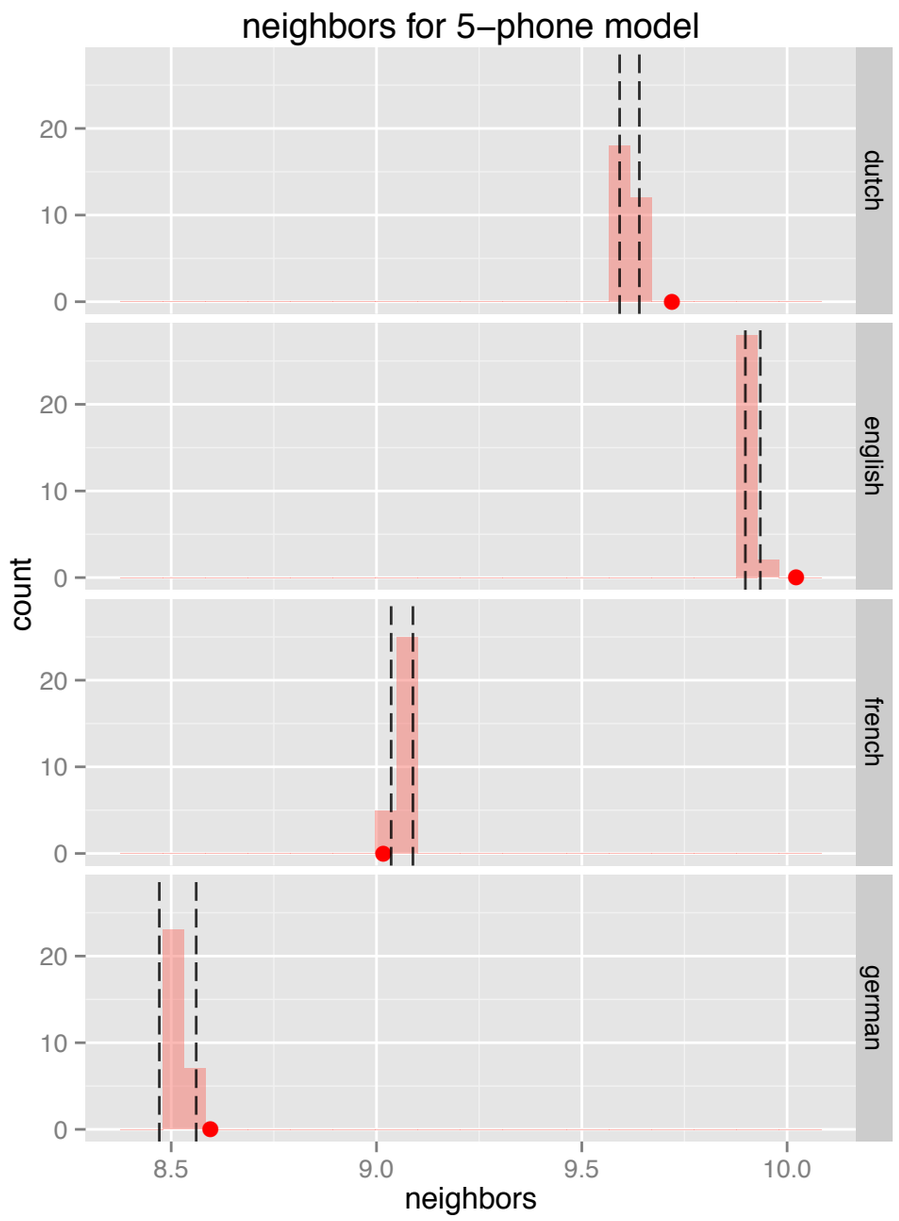
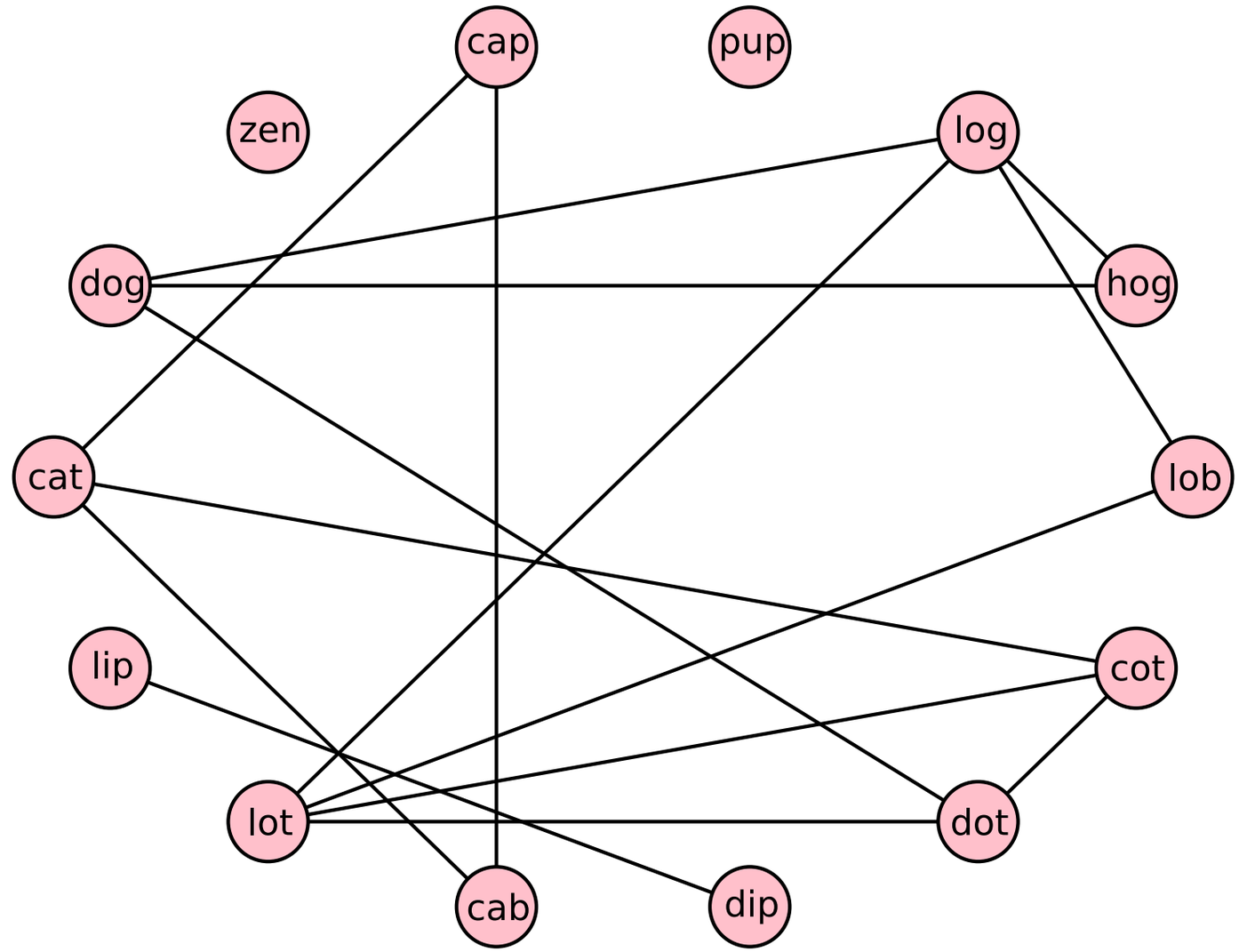


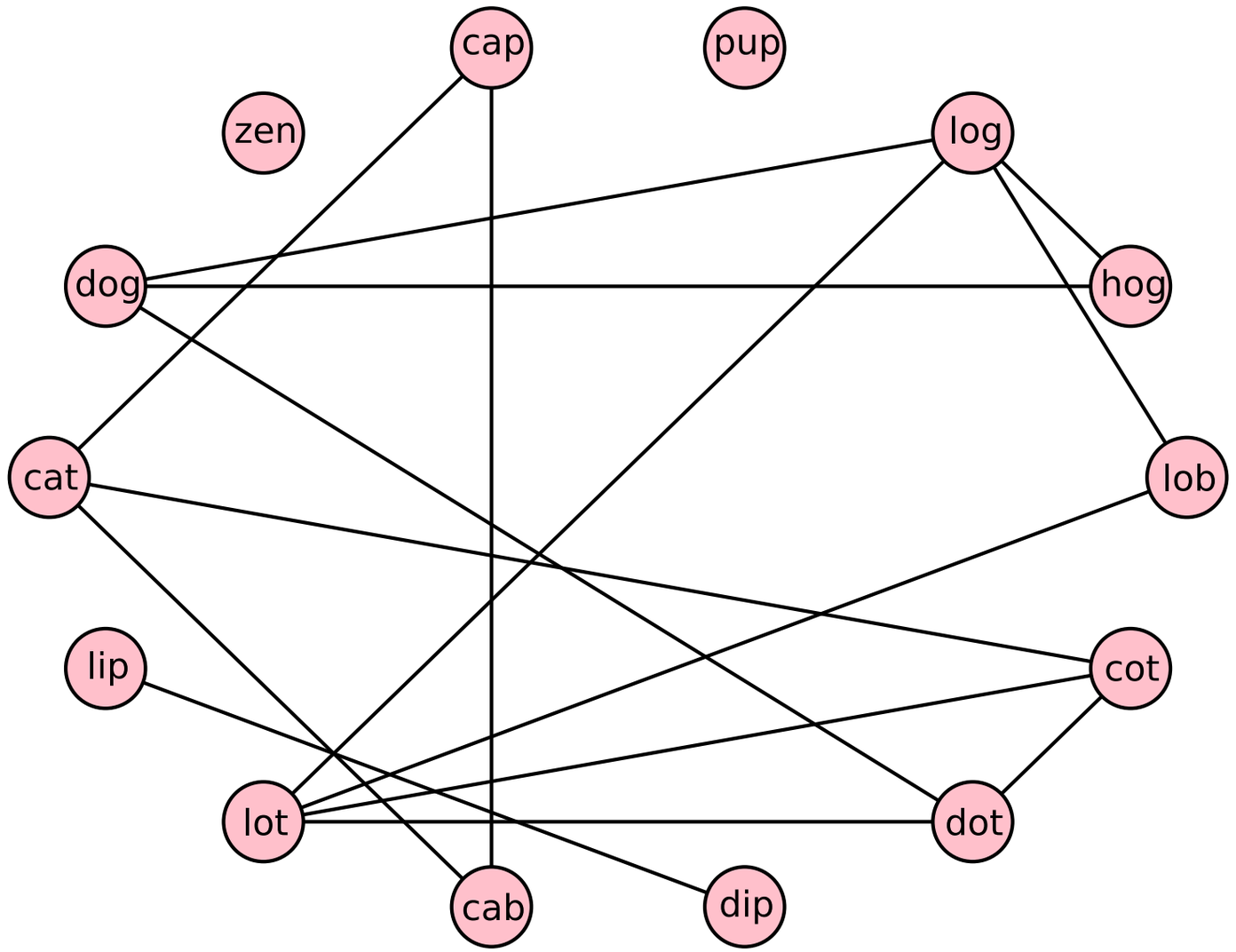


Results: Network measures

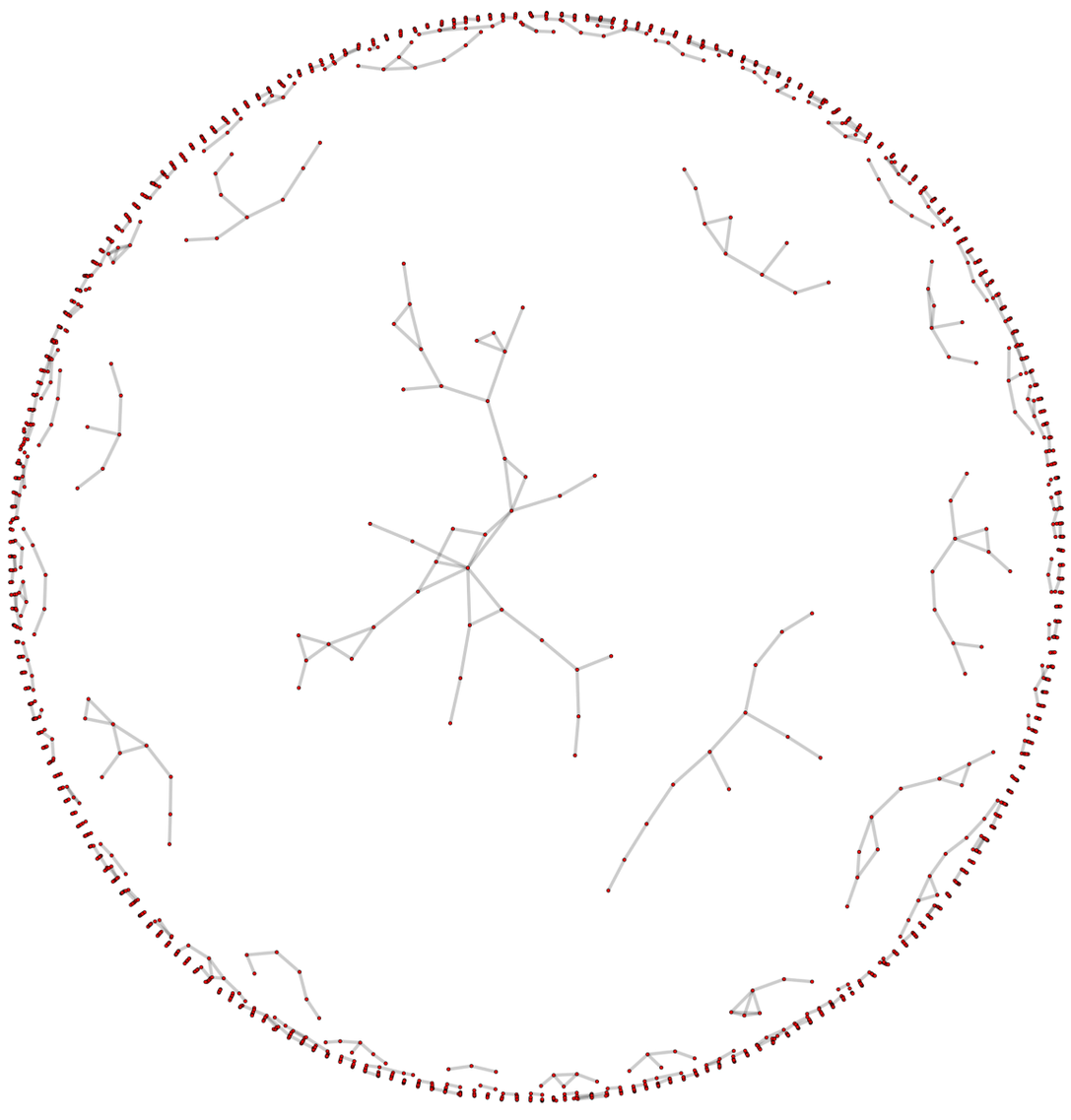


Results: Network measures

Connect any 2 nodes that are a minimal pair



1-phone model



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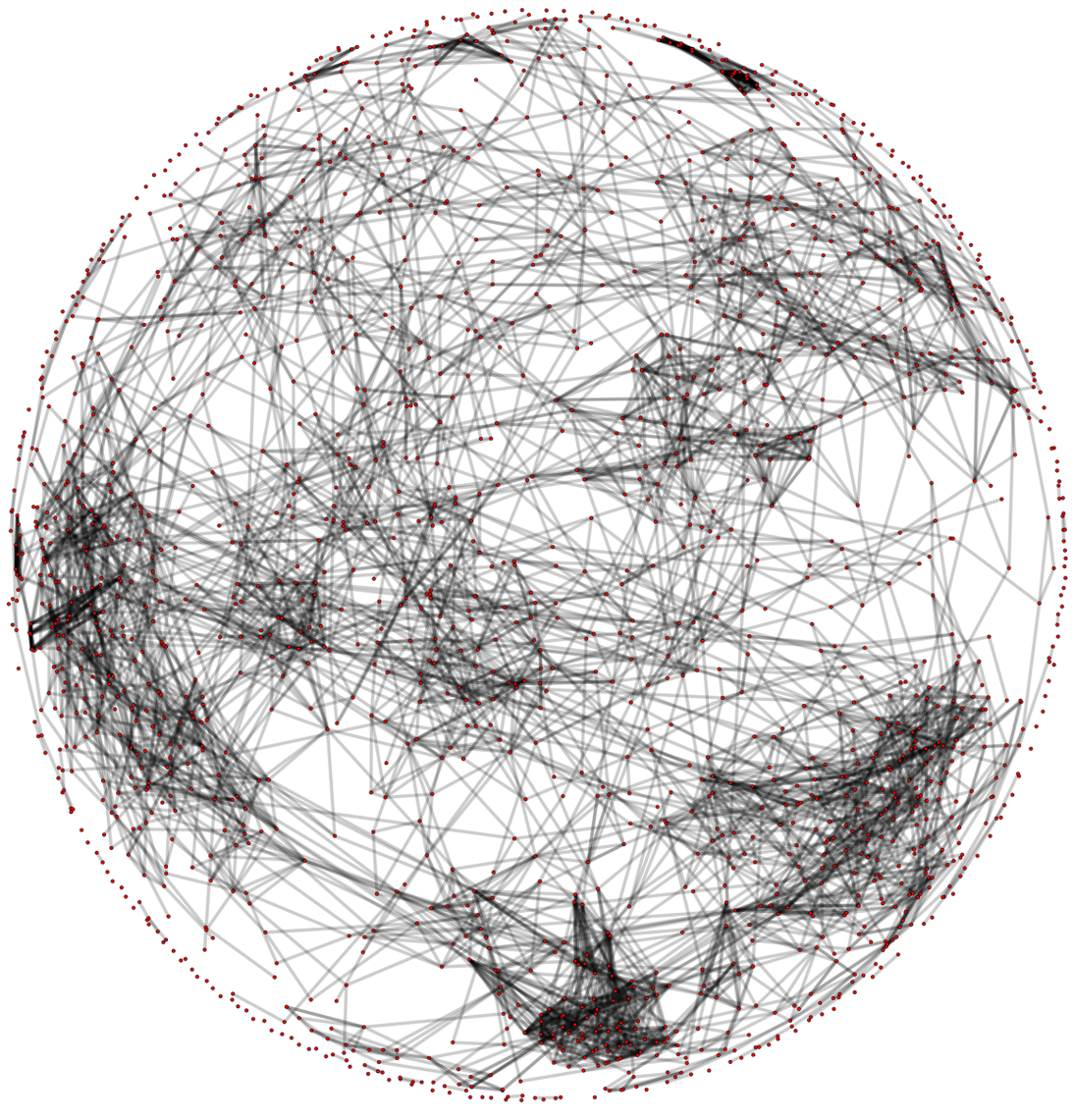
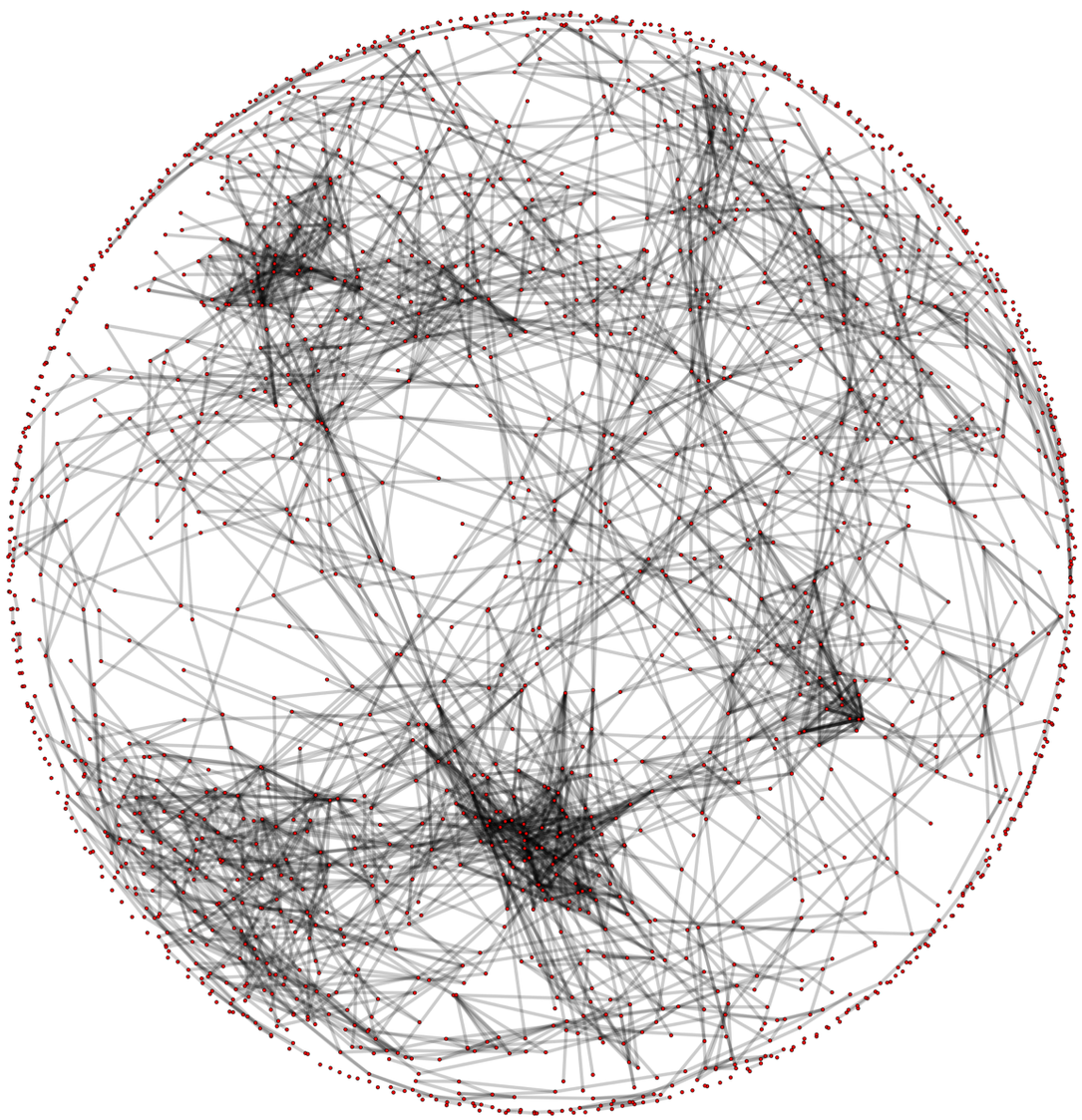
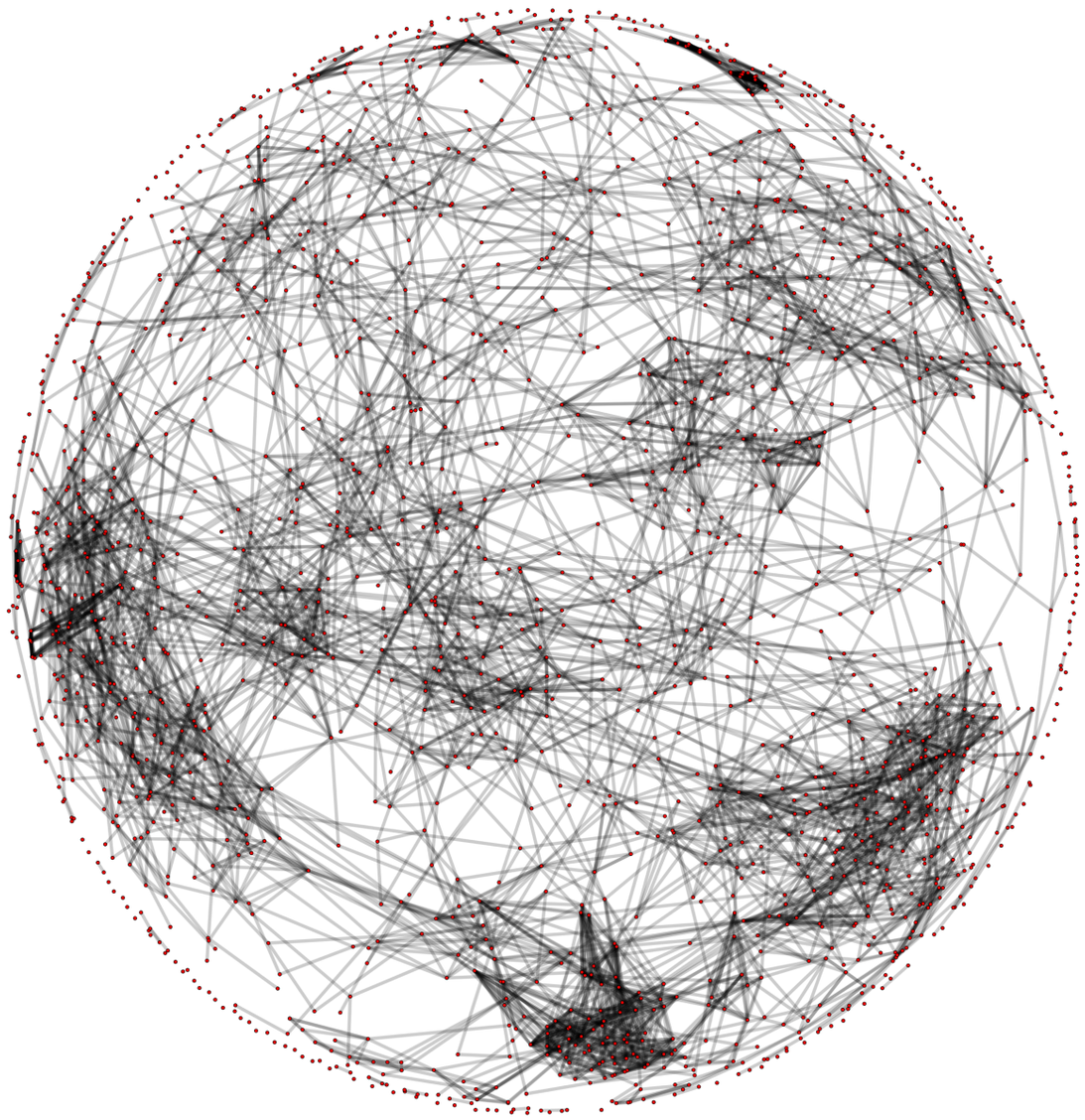


real lexicon

2-phone model

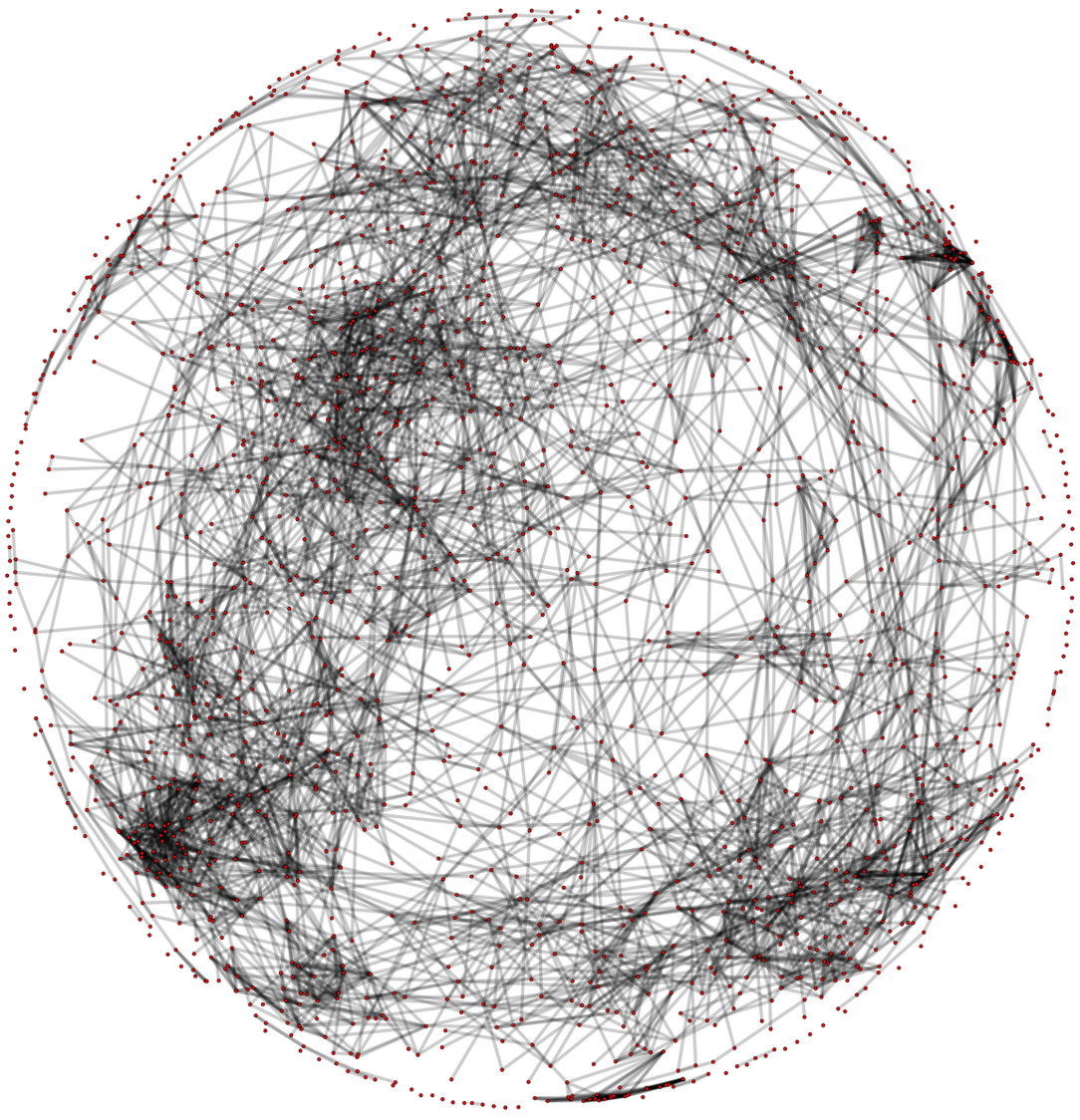


2-phone model



real lexicon

3-phone model



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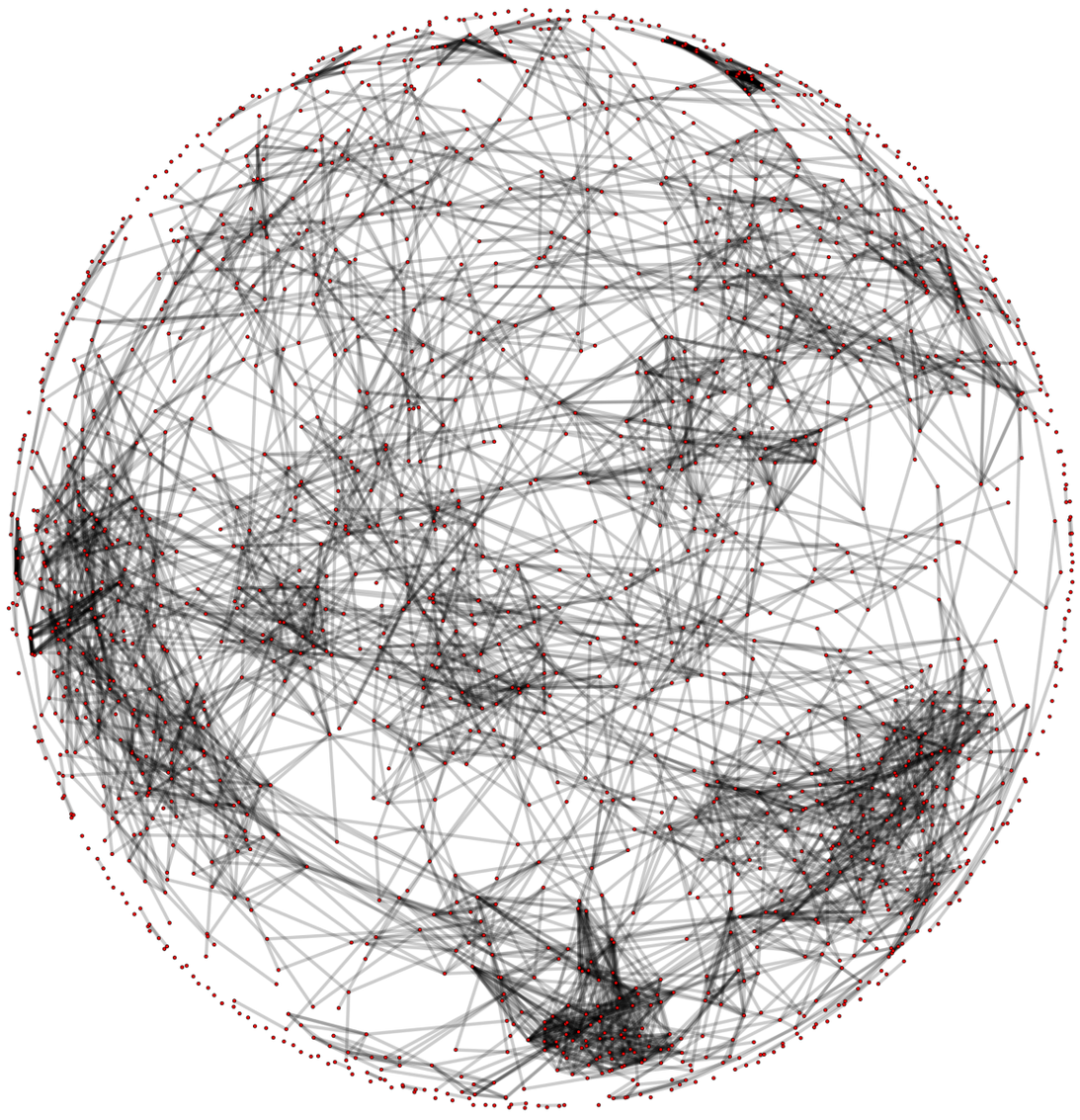
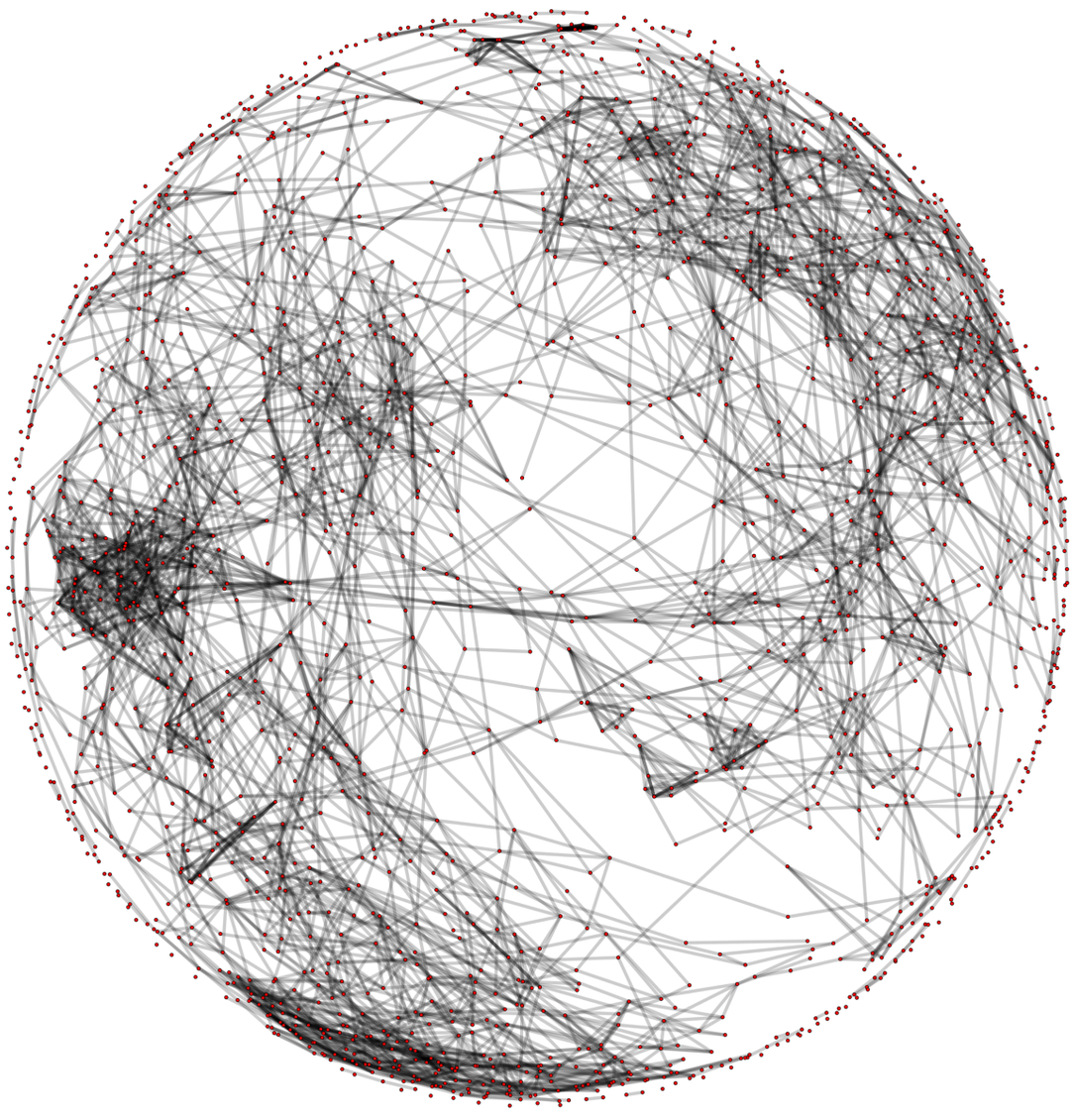
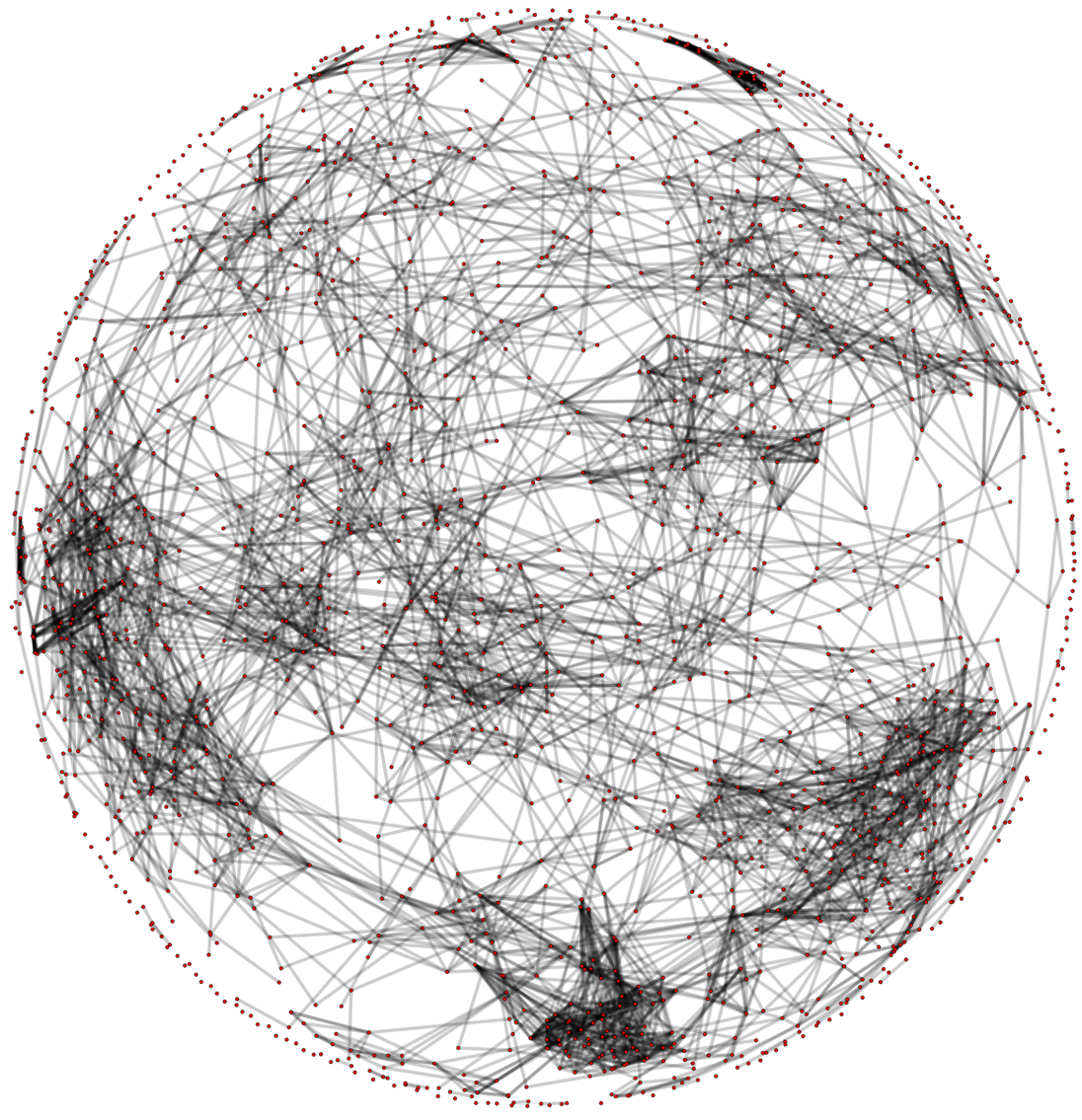


real lexicon

4-phone model

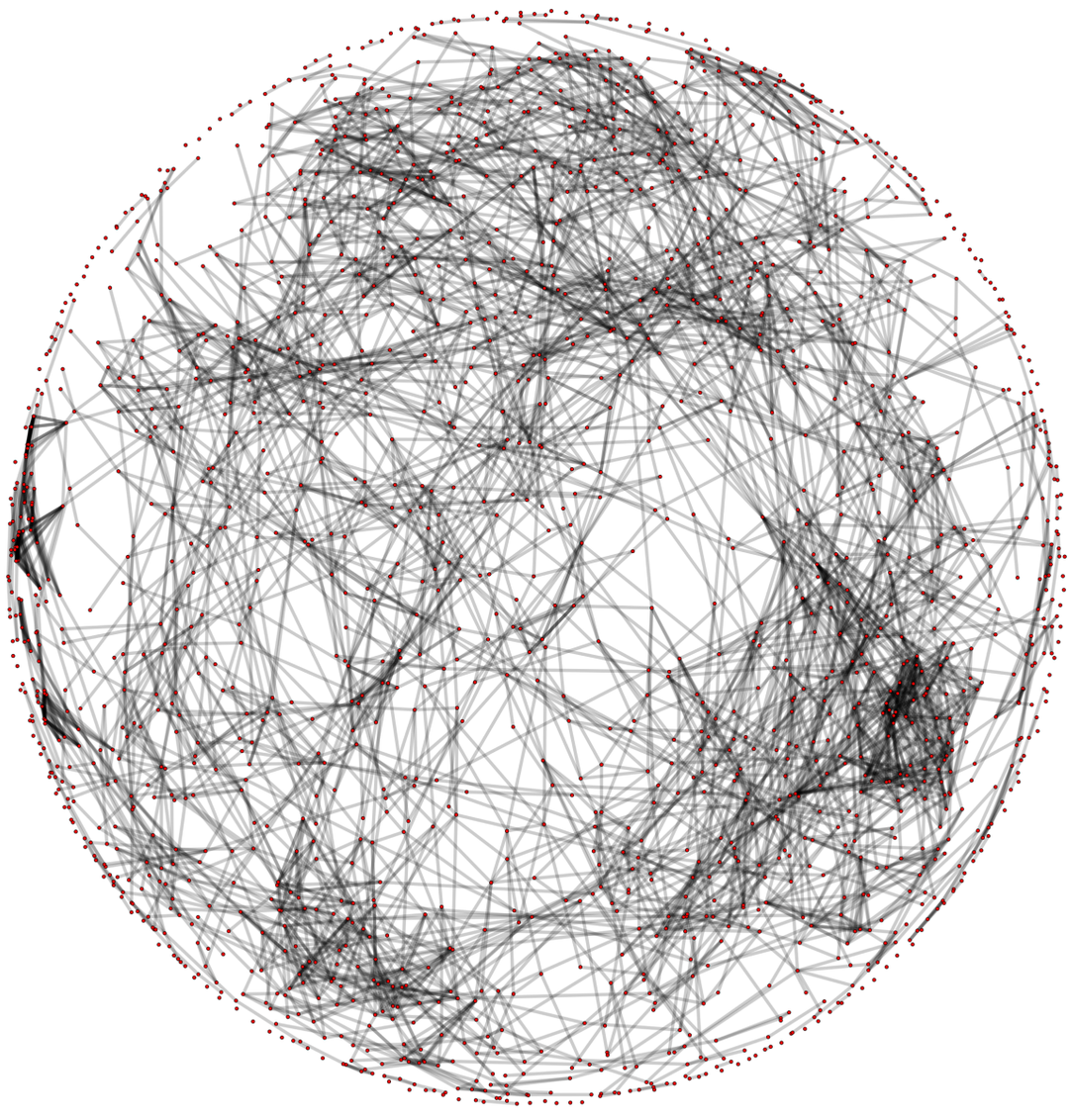


4-phone model

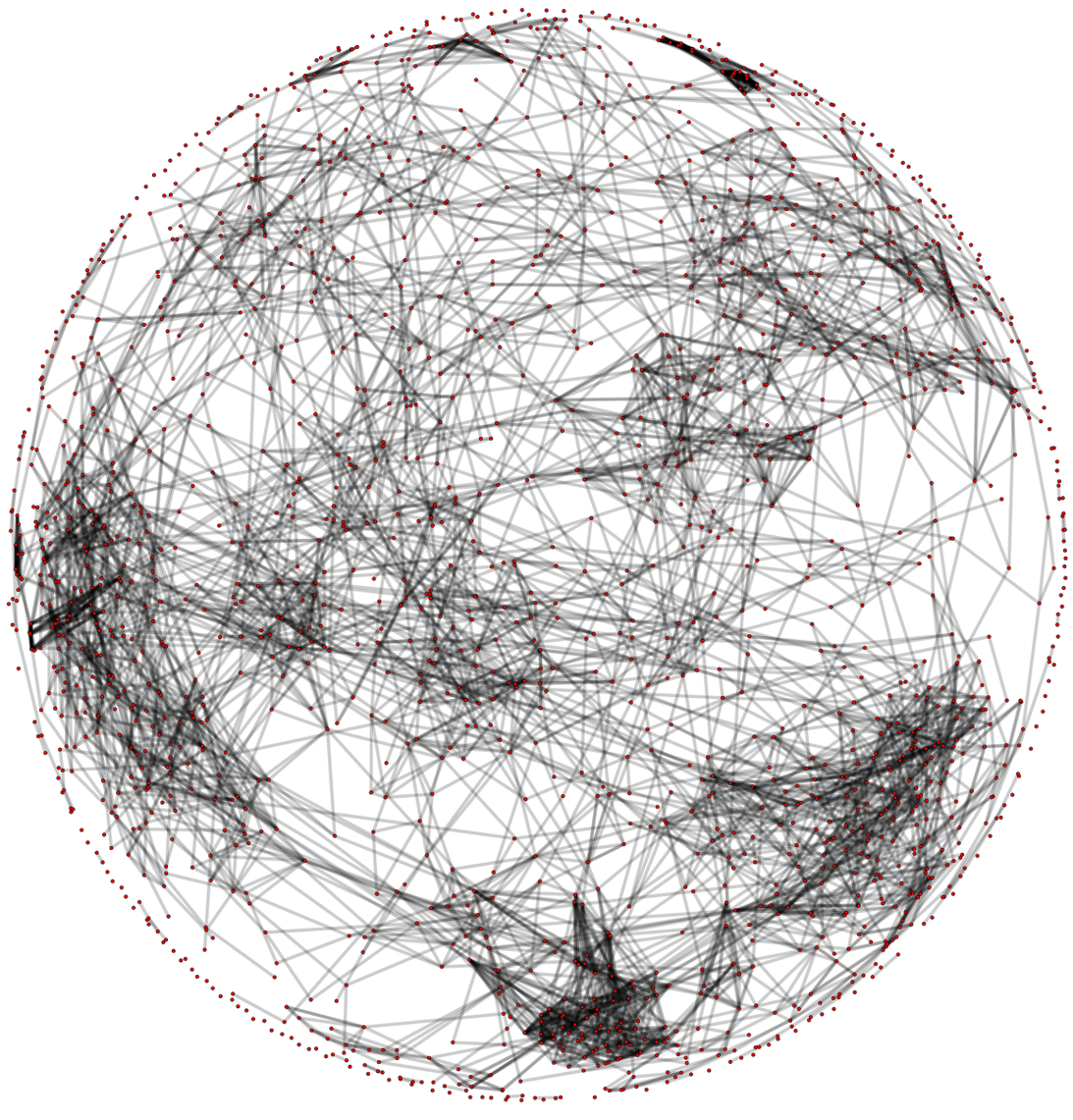


real lexicon

5-phone model

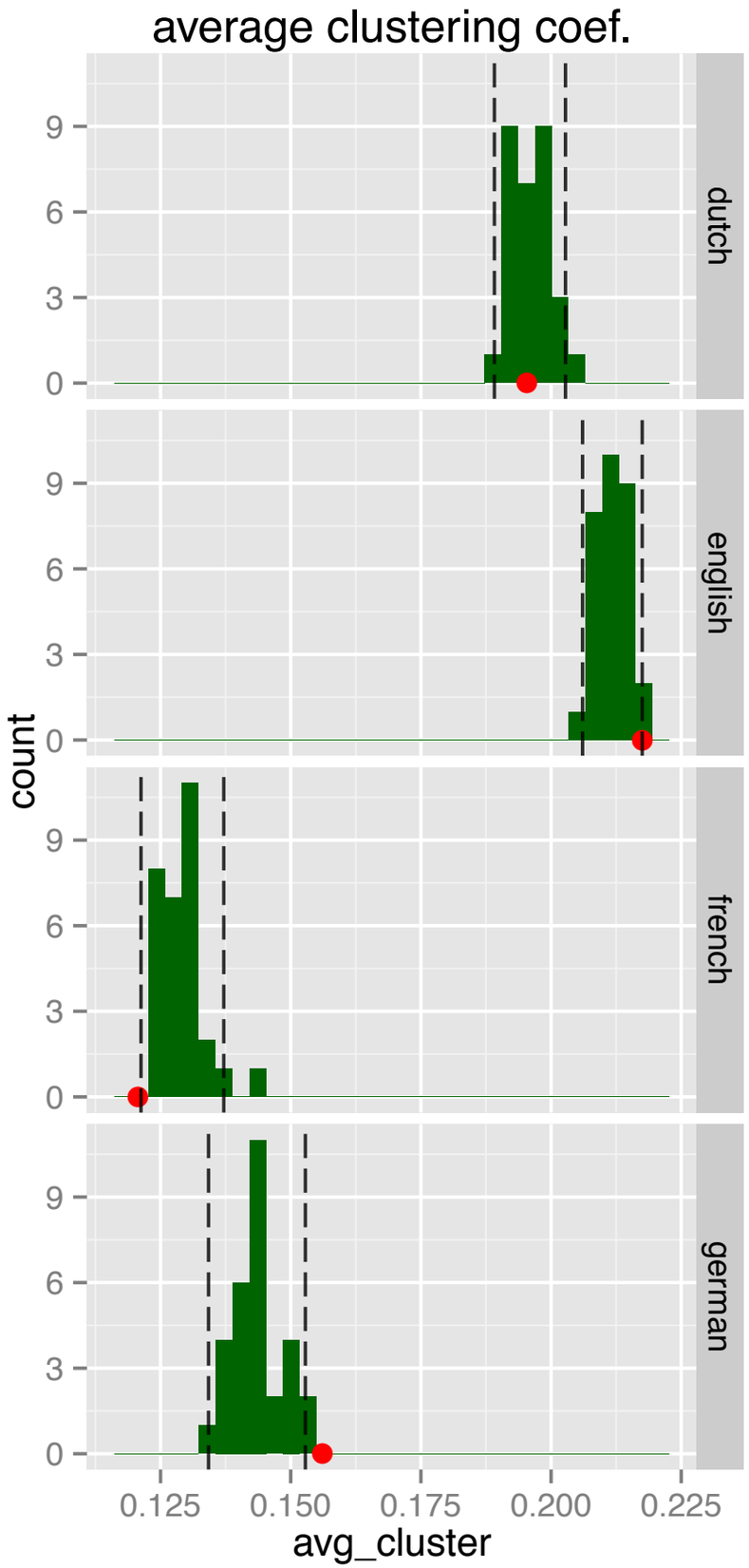


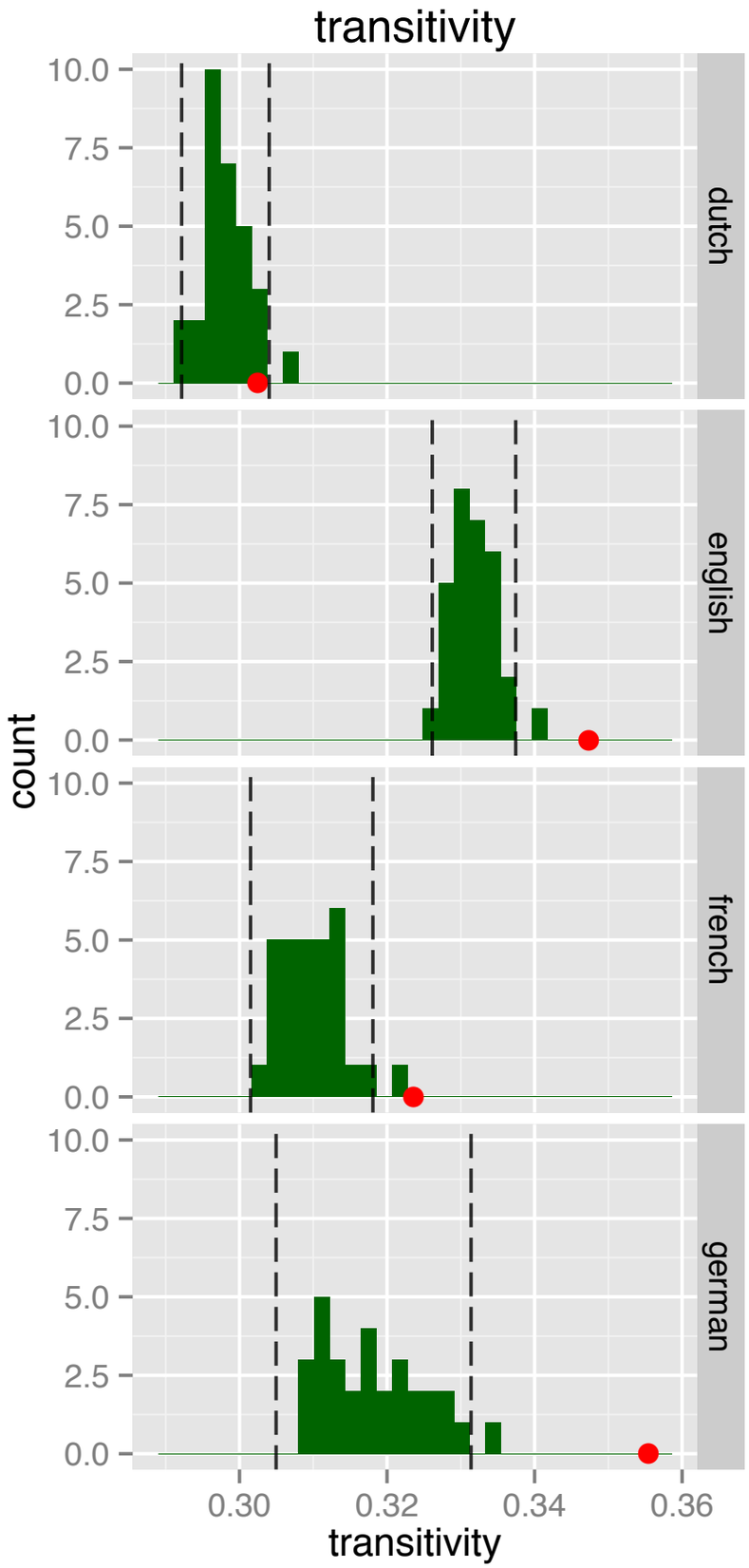
5-phone model



real lexicon

most network measures suggest clumpiness





Summary of null lexicons

- With the sometimes exception of French (and possibly word onset/coda measures), most real lexicon measures appear to be clumpy relative to the best baseline.

- Result not from morphology or meaningful subunits

- Not from sound to sound transition probability

- Ongoing work: effects of semantics? Effects of etymology.

Summary

- Info/information: Communicative pressures act on word length distributions.

- Wikipedia results: The lexicon is clumpy.

- Null lexicon results: Even compared to plausible baselines, the lexicon seems clumpy.

- Future work: Building models, exploring the underlying processes that give rise to the structure seen here.

Thanks!

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- And members of Tedlab: Tim O’Donnell, Melissa Kline, Leon Bergen, Laura Stearns