The emergence of categorical and compositional structure in an open-ended meaning space

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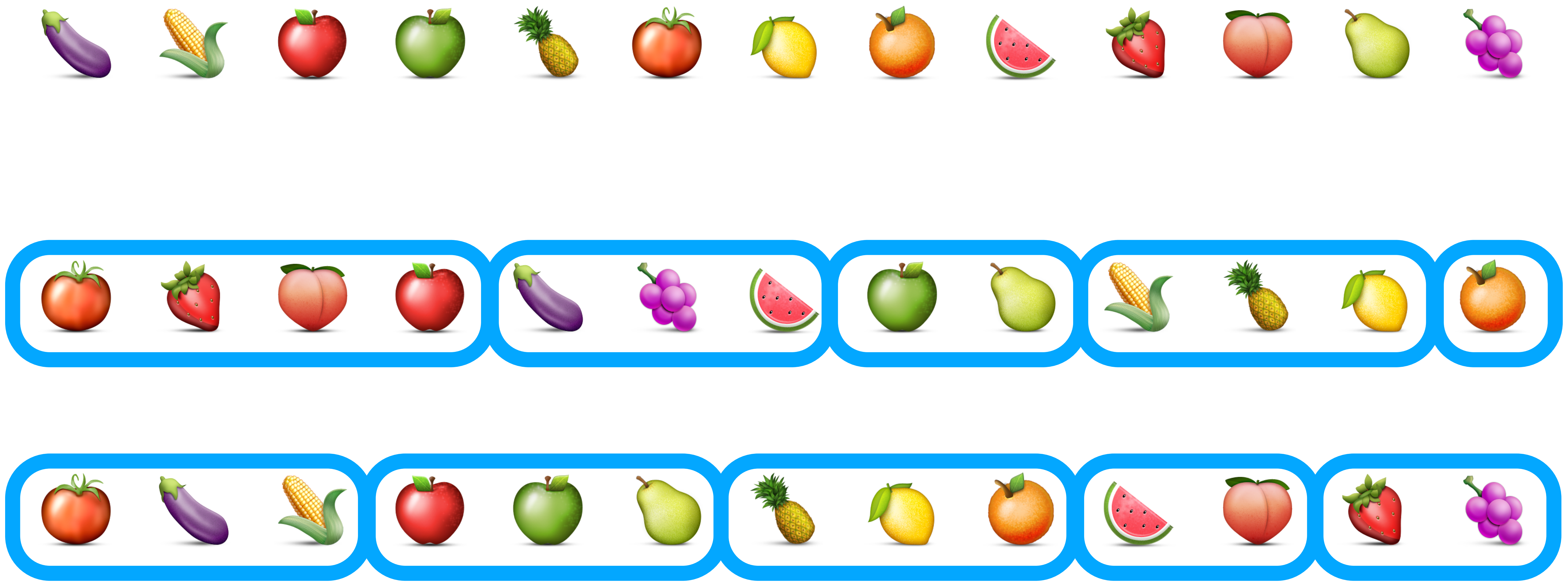
Categorical structure



By sufficiently aligning on a particular arbitrary system of meaning distinctions, two members of a population can rely on this shared **categorical structure** to successfully communicate.

Compositional structure

Meaning of the whole = Meaning of the parts + The way in which the parts are combined

	Blue	Green
🍎	poi	gugi
🍌	meshin	tikolu

	Blue	Green
🍎	blueapple	greenapple
🍌	bluebanana	greenbanana

Compositionality allows languages to be maximally expressive, while also maximally compressible (Kirby, Tamariz, Cornish, & Smith, 2015).

Iterated learning

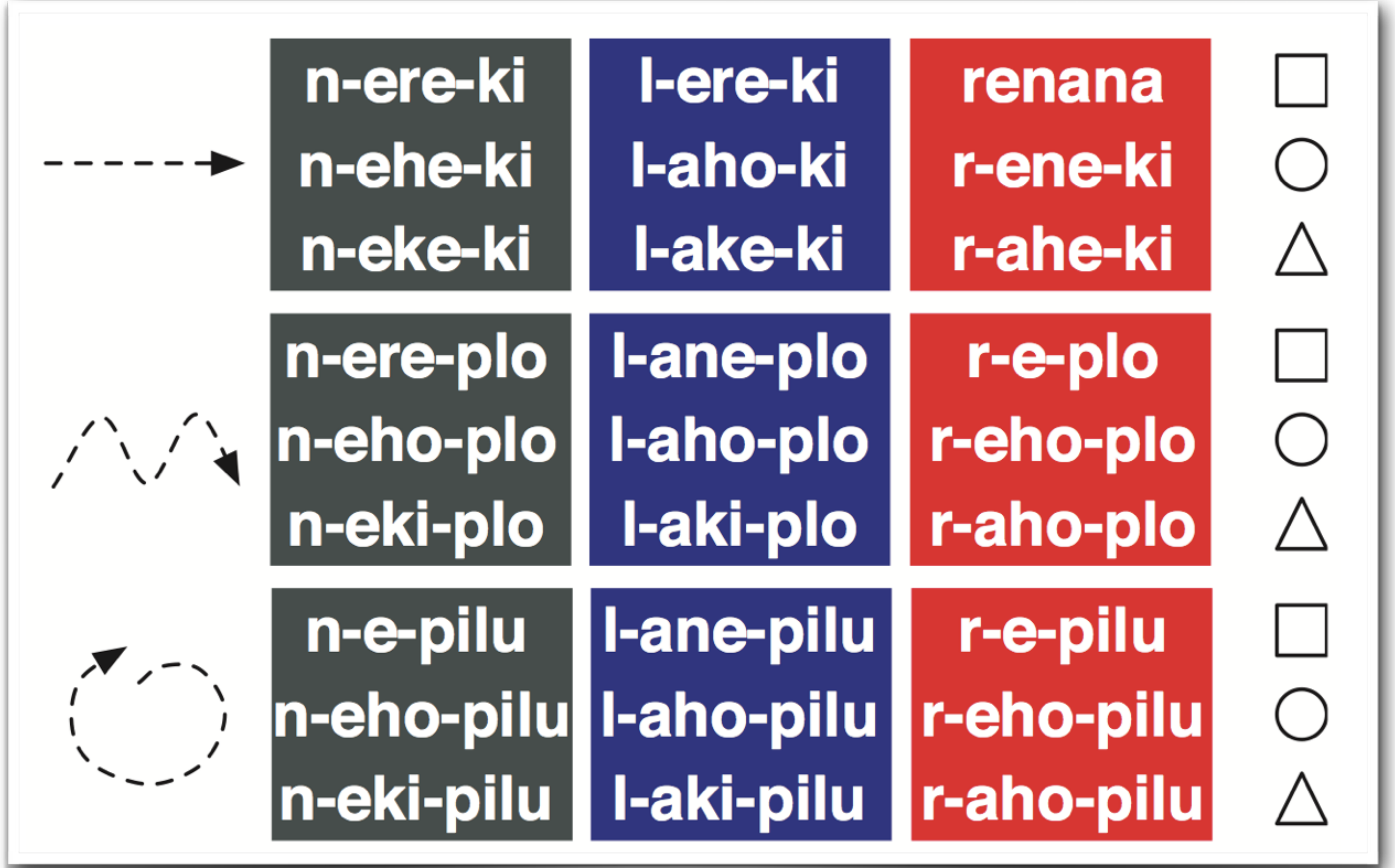
Emergence of compositional structure
in the signal space

e.g. Kirby, Cornish, & Smith (2008)

Emergence of categorical structure
in the meaning space

e.g. Silvey, Kirby, & Smith (2013)

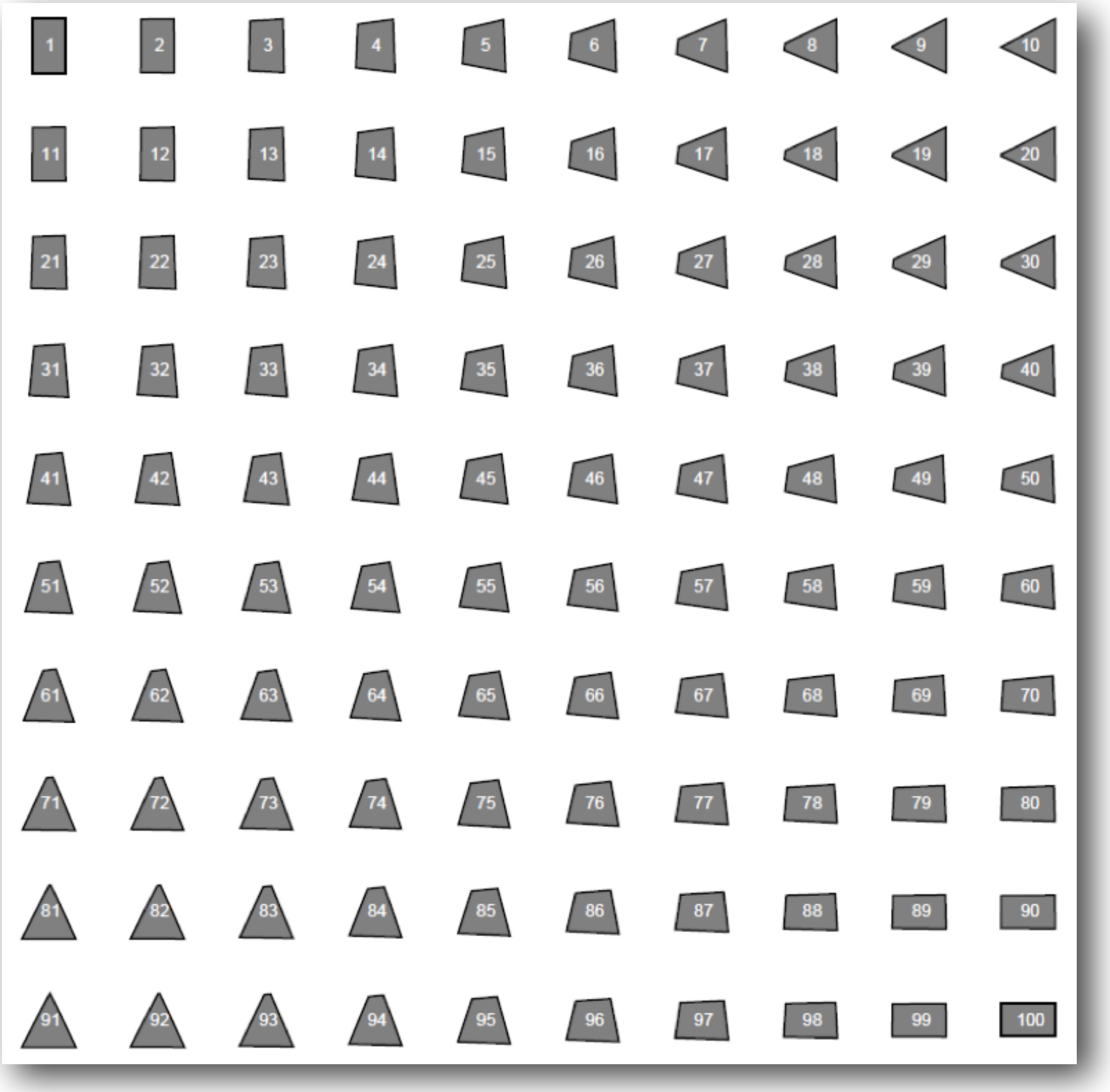
Discrete meaning spaces



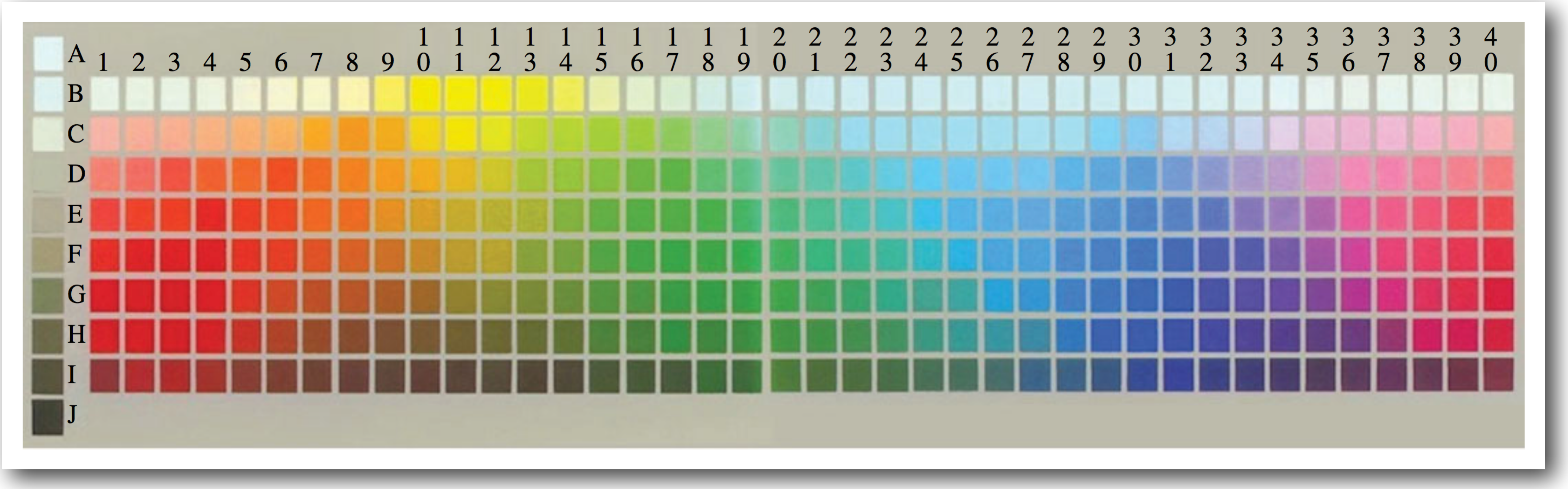
Kirby, Cornish, & Smith (2008)

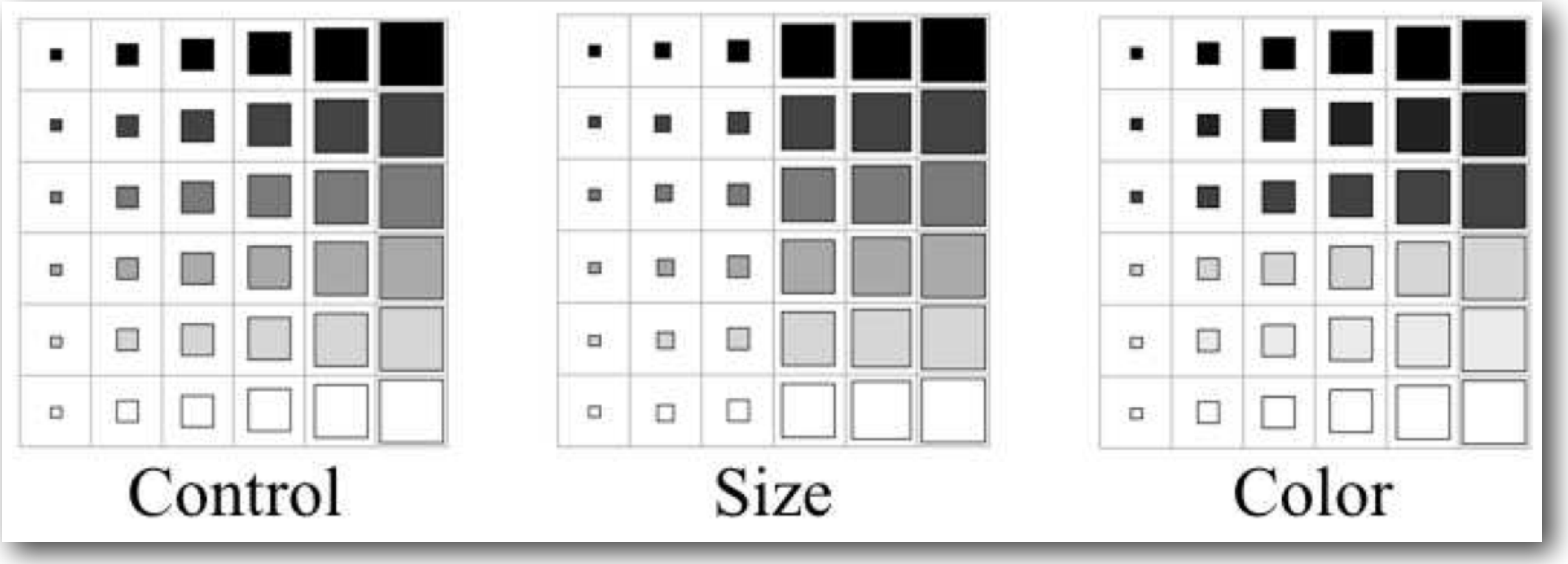
Continuous meaning spaces

Matthews (2009)

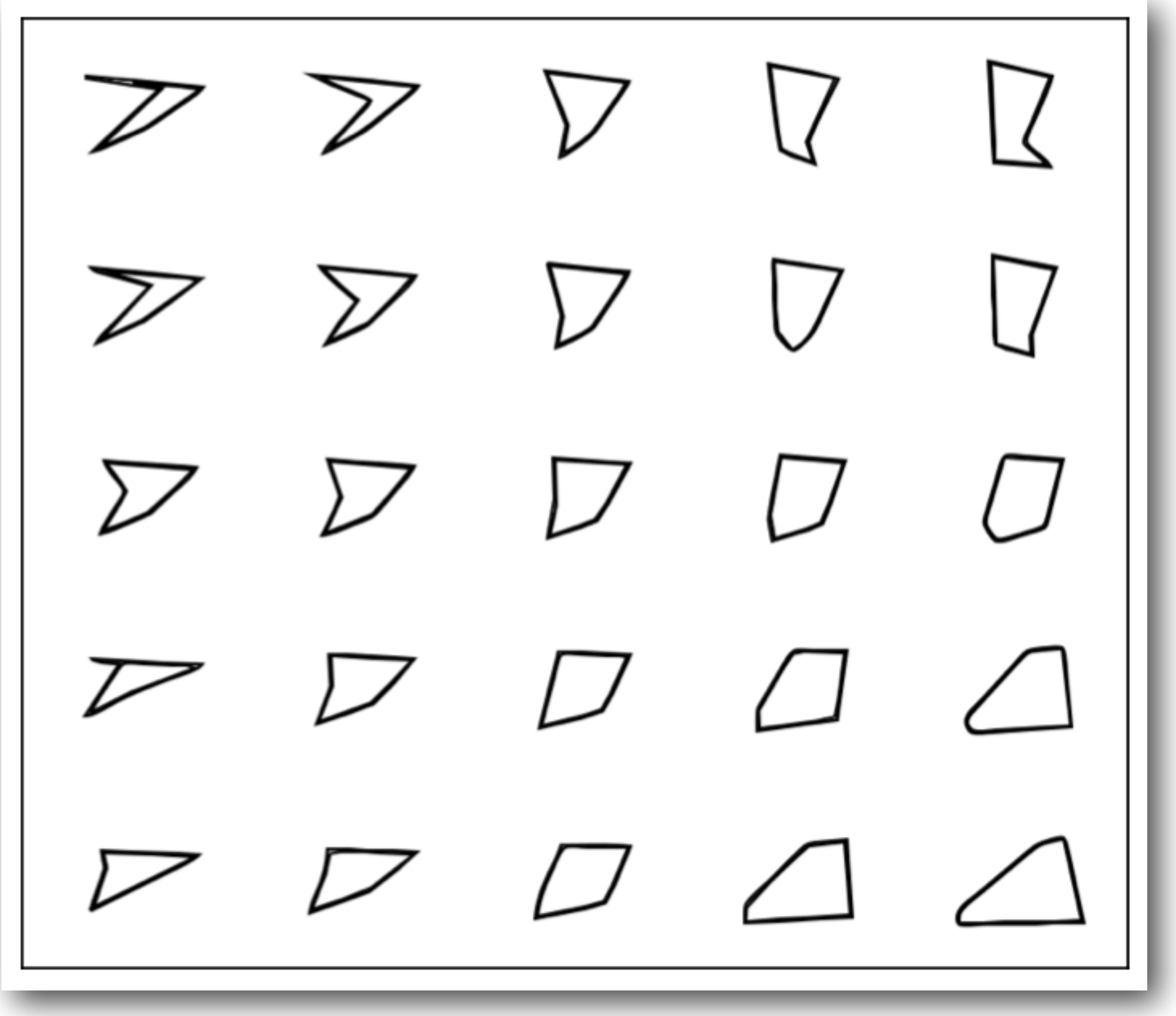


Xu, Dowman, & Griffiths (2013)





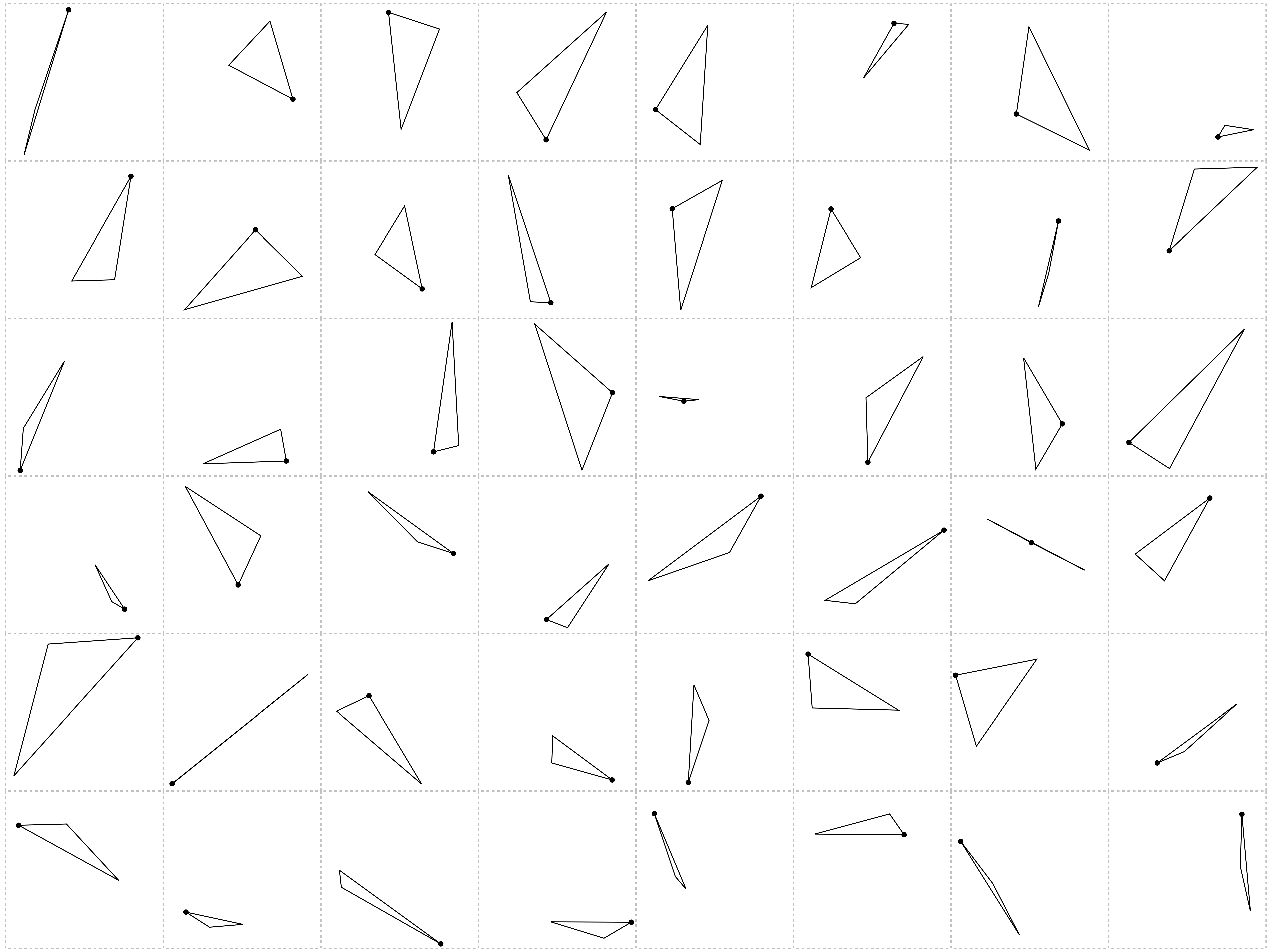
Perfors & Navarro (2014)



Silvey, Kirby, & Smith (2013)

Can we see the emergence of *compositional* structure under an *open-ended* meaning space?

Triangle stimuli



Complex dimensions: Many possible dimensions to the space

Continuous: On each dimension, the triangle stimuli vary over a continuous scale

Vast in magnitude: 6×10^{15} possible triangle stimuli

Not pre-specified by the experimenter: no particular hypothesis about which features participants would find salient

Hypotheses

Hypothesis 1: categorical structure will emerge in the meaning space

Hypothesis 2: compositional structure will emerge in the signal space

Hypothesis 3: the languages will become easier to learn as a consequence of H1 and/or H2

Experiment I

Participants

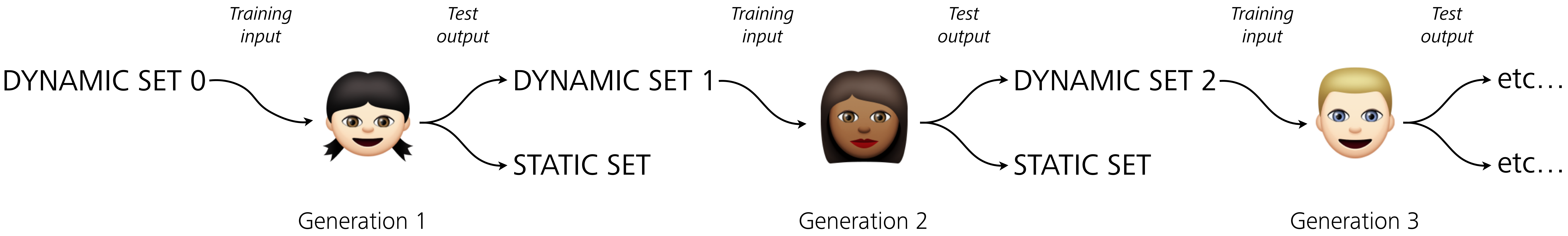
40 participants recruited via MyCareerHub

Native English speakers

Paid £5.50, with opportunity to win £20 Amazon voucher

Learning the language of the Flatlanders, who have many words for triangles

Transmission paradigm



Training phase

Stage 1: Training

You will see a series of triangles along with the words used to describe them. After every third triangle, you will see one of those three triangles again, and you must type in the word you just learned for it. You will be told whether or not you got it right.

Try to learn the words for the triangles as best as you can, as you will use them to communicate with your partner later on.

Press the Enter key when you're ready to begin training

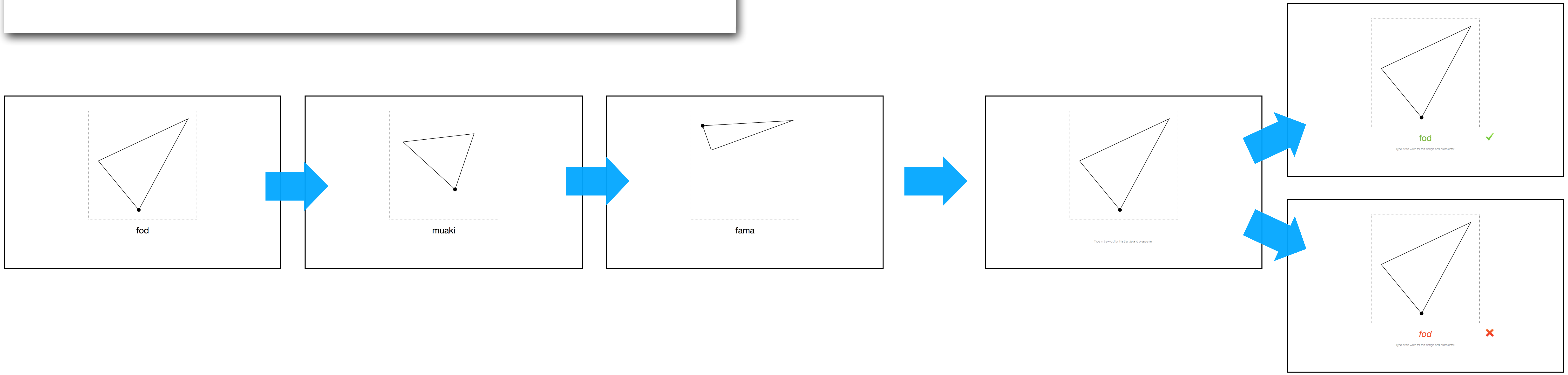
Training material: 48 items in previous dynamic set

144 total trials

Each item presented three times

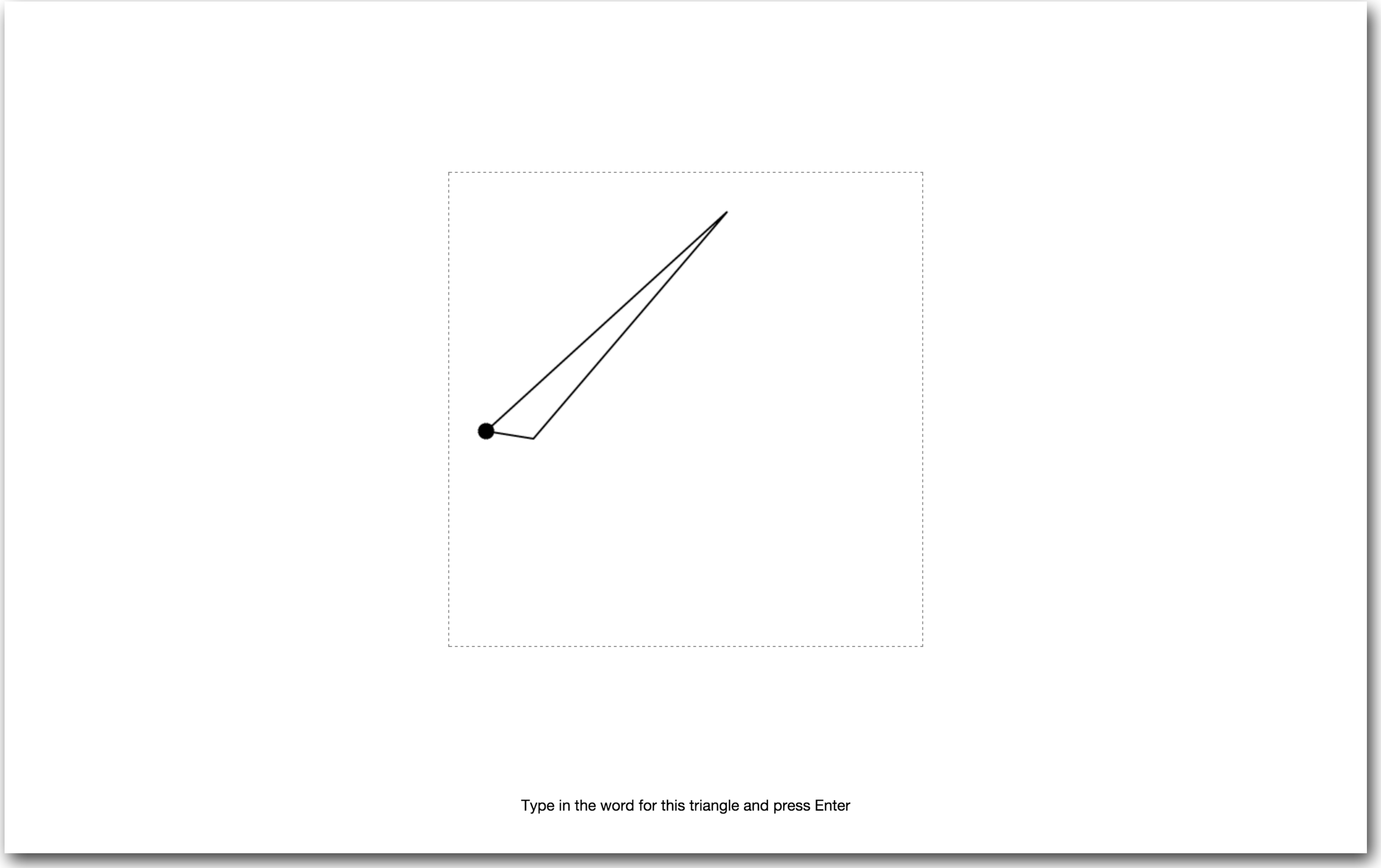
Each item mini-tested once

Feedback on correct answer



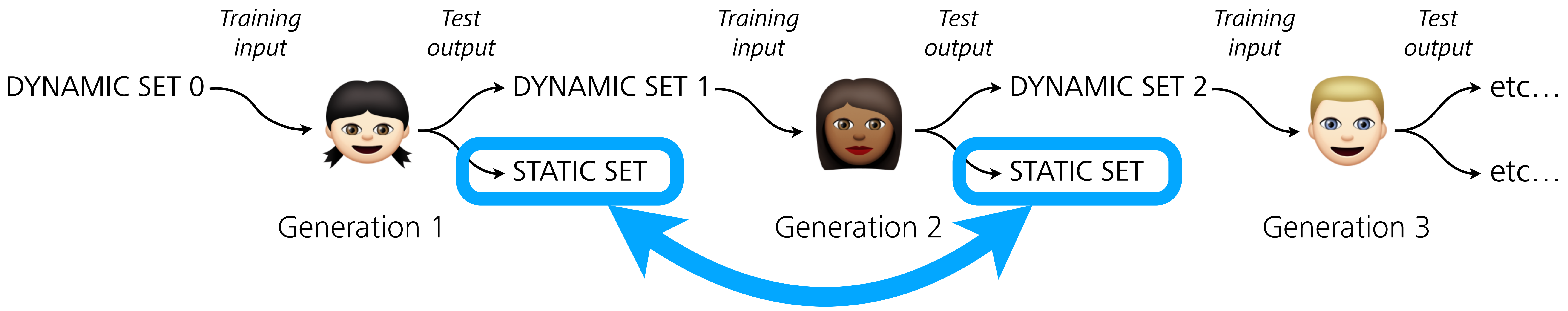
× 48

Test phase



× 96

Measure of learnability



Transmission error is mean normalized Levenshtein distance:

$$e(i) = \frac{1}{|M|} \sum_{m \in M} \frac{\mathrm{LD}(s_i^m, s_{i-1}^m)}{\max(\mathrm{len}(s_i^m), \mathrm{len}(s_{i-1}^m))}$$

"Learnability" is transmission error adjusted for chance using a Monte Carlo method.

Measure of structure

The languages are essentially mappings between signals and meanings

To measure structure, we correlate the dissimilarity between pairs of strings with the dissimilarity between pairs of triangles for all $n(n-1)/2$ pairs

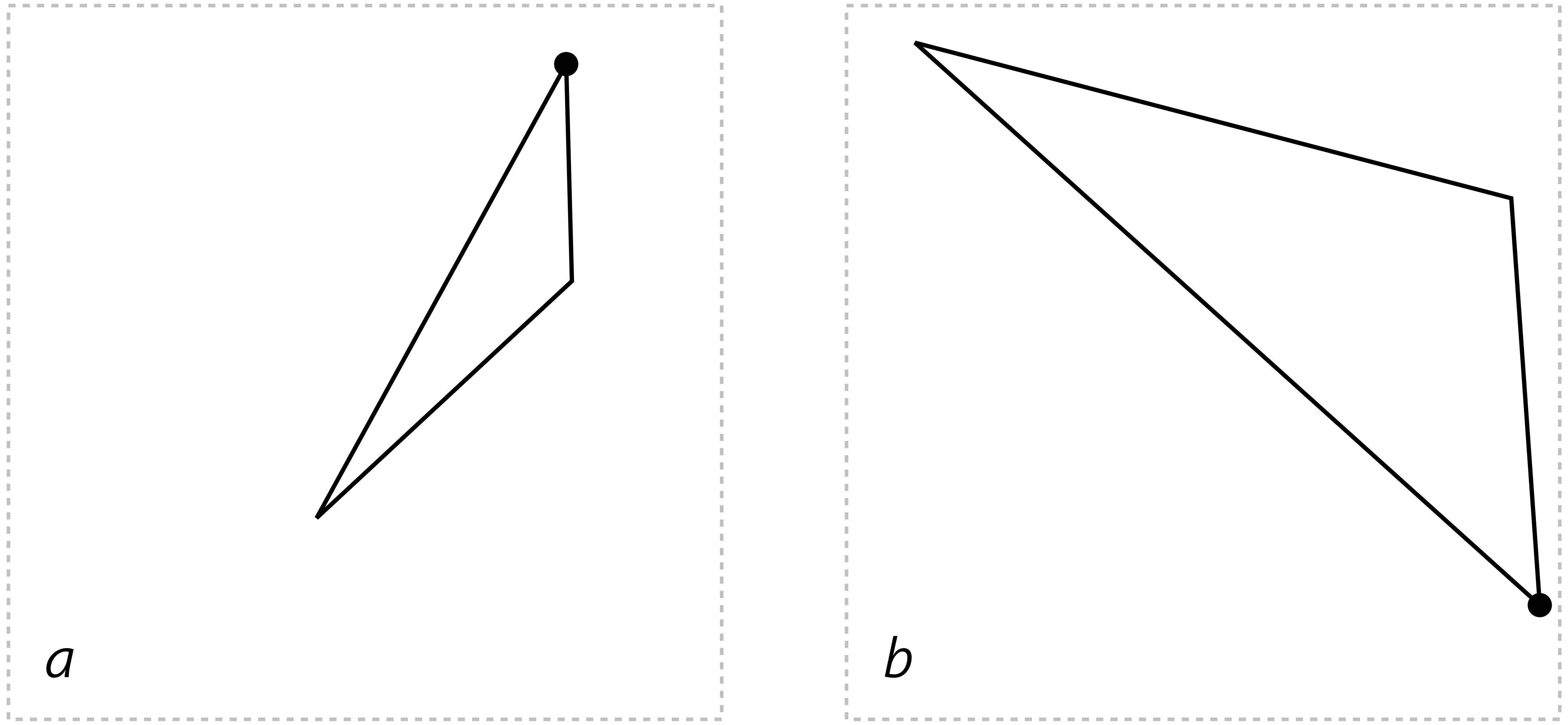
We then perform a Mantel test (Mantel, 1967) which compares this correlation against a distribution of correlations for Monte-Carlo permutations of the signal-meaning pairs

This yields a standard score (z-score) quantifying the significance of the observed correlation

Normalized Levenshtein distance used to measure the dissimilarity between pairs of strings

Triangle dissimilarity metric

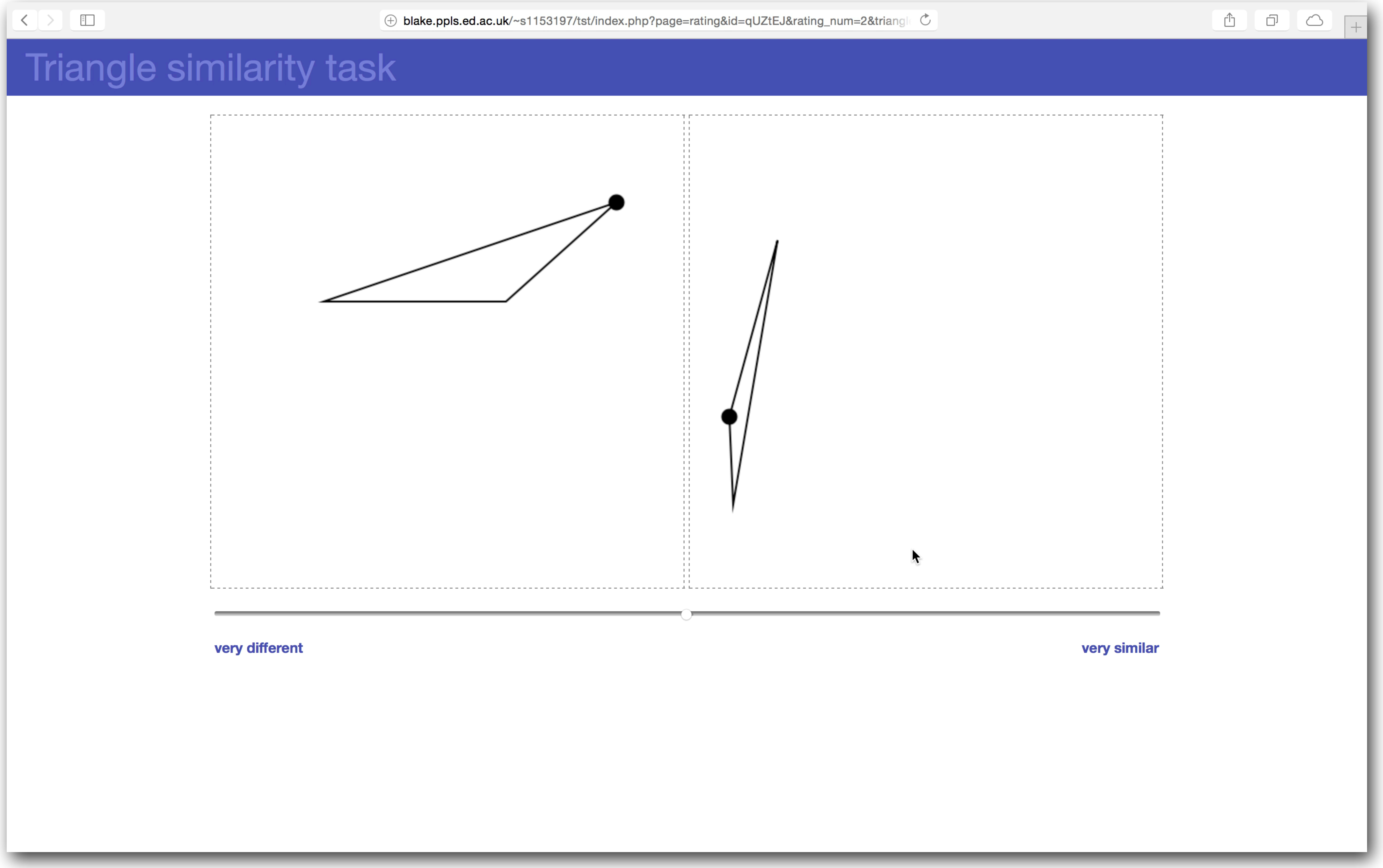
Size features
1. Area
2. Perimeter
3. Centroid size
Positional features
4. Location of dot on *x*-axis
5. Location of dot on *y*-axis
6. Location of centroid on *x*-axis
7. Location of centroid on *y*-axis
Orientational features
8. Radial distance from North by dot
9. Radial distance from North by thinnest angle
Shape features
10. Angle of thinnest vertex
11. Angle of widest vertex
12. Standard deviation of angles
Bounding box features
13. Distance from dot to nearest corner
14. Distance from dot to nearest edge
15. Mean distance from vertices to nearest corner
16. Mean distance from vertices to nearest edge



Euclidean distance through the feature space:

$$d(a, b) = \sqrt{\sum_{f \in F} (a_f - b_f)^2}$$

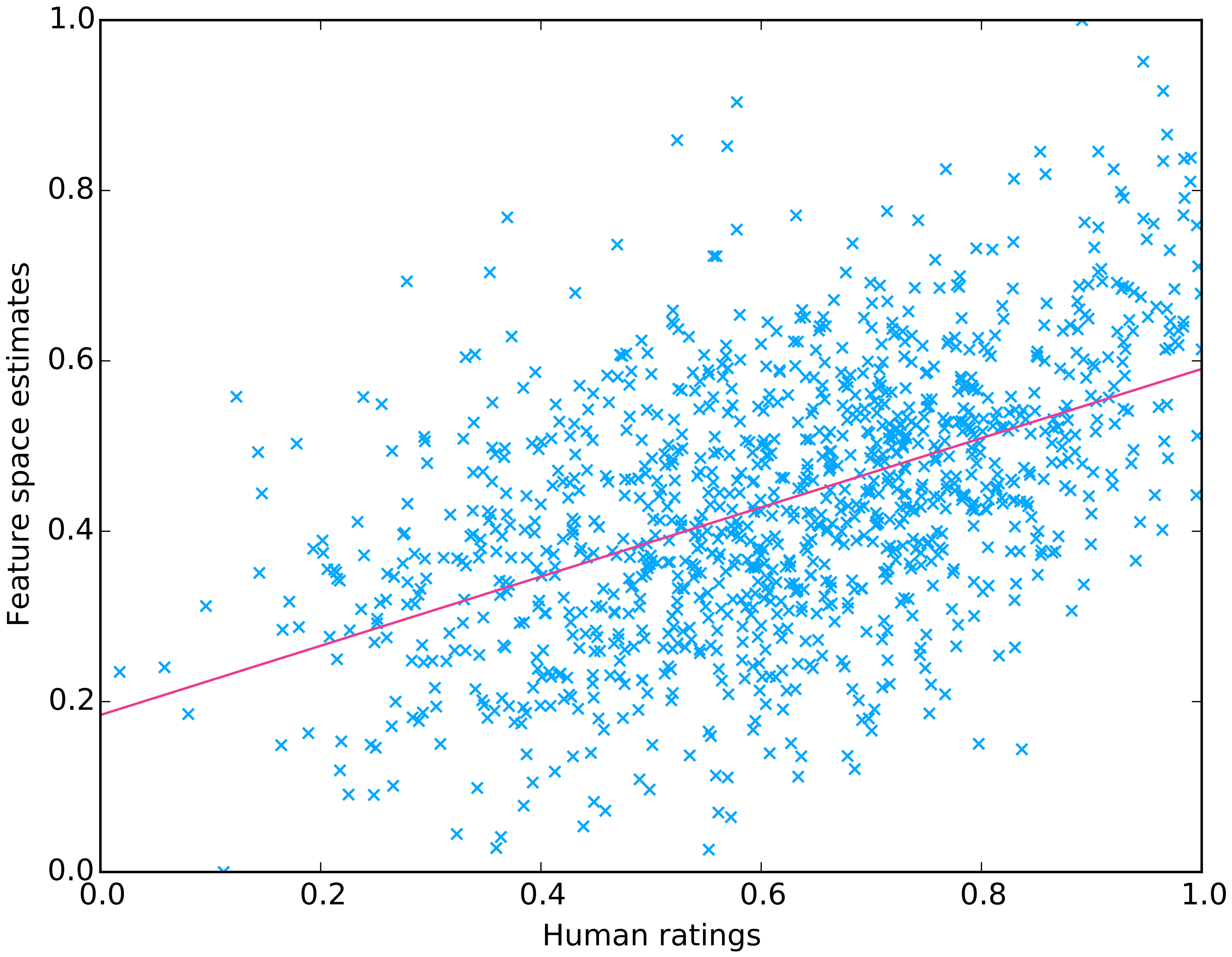
Online dissimilarity experiment



96 participants, paid $0.50

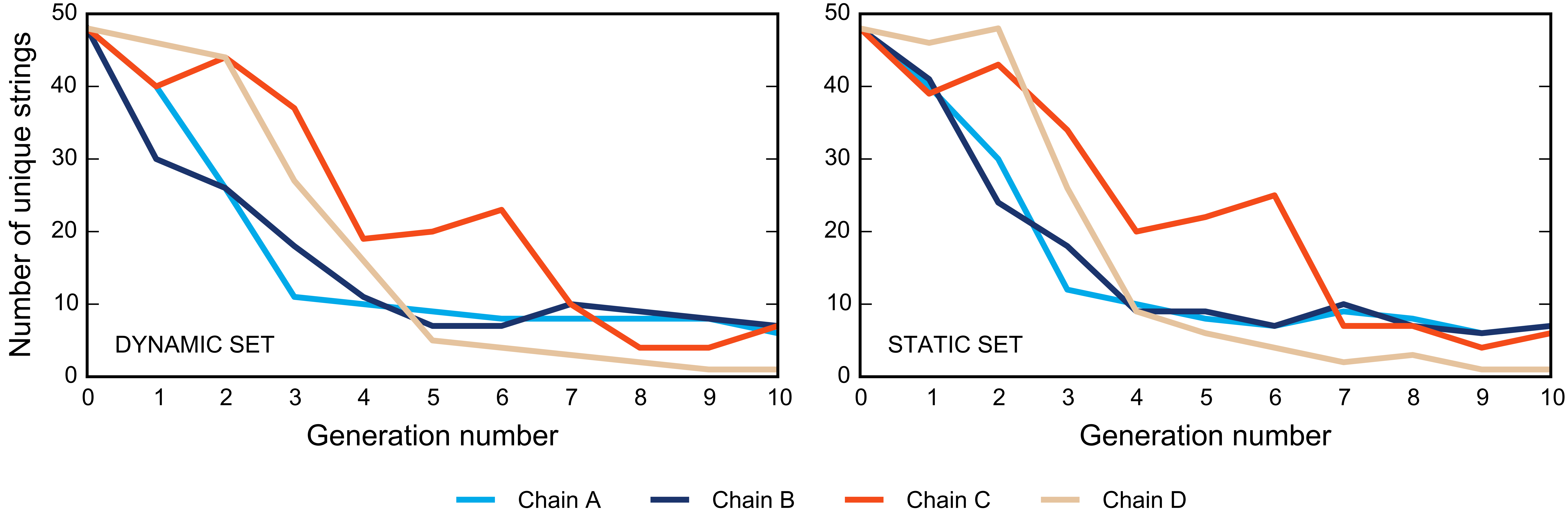
12,767 total ratings (11.3 per stimulus pair)

Mean rater agreement: 0.7

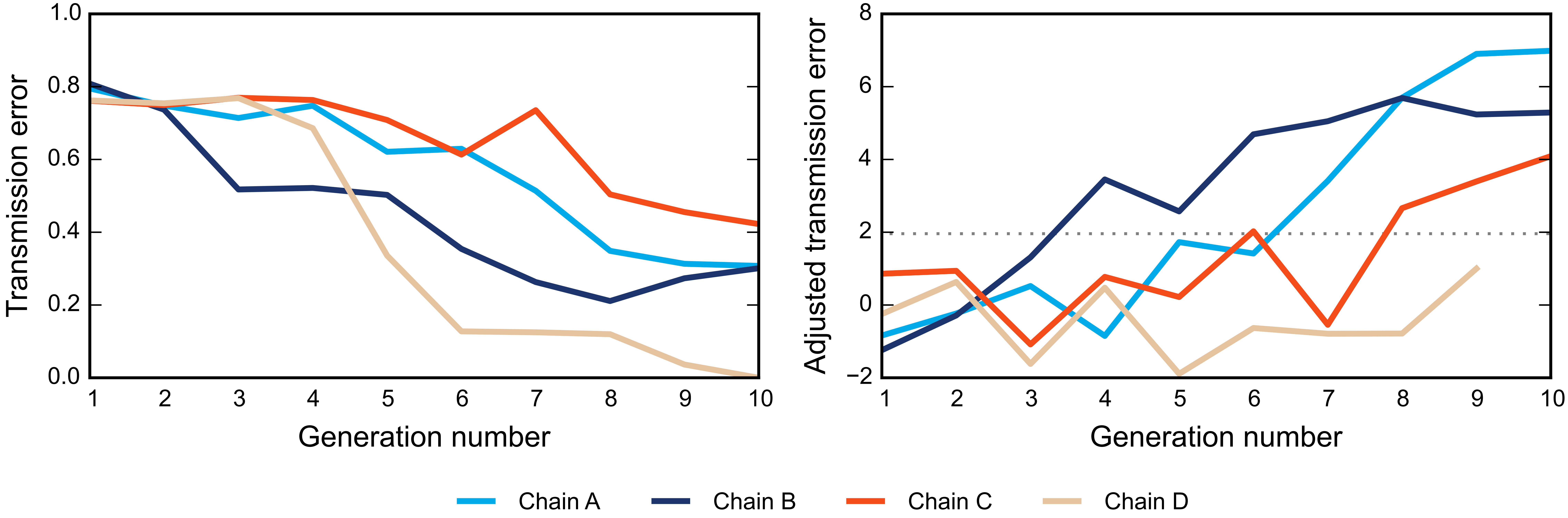


$r = 0.499$, $n = 1128$, $p < 0.001$

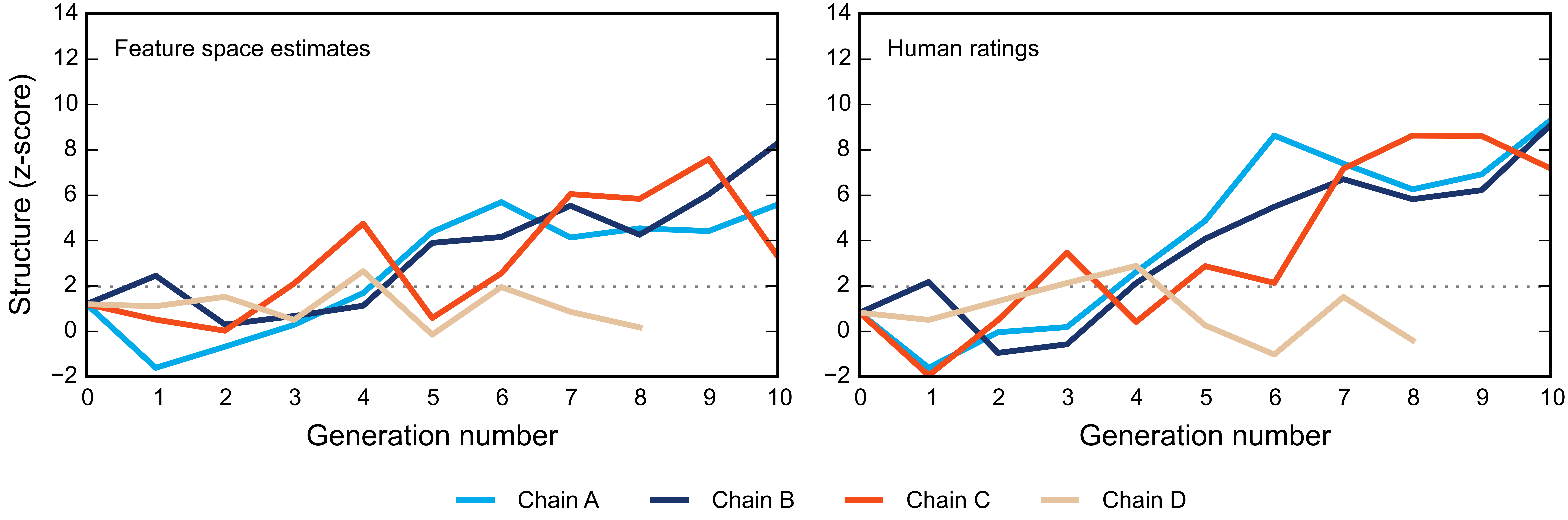
Expressivity



Learnability

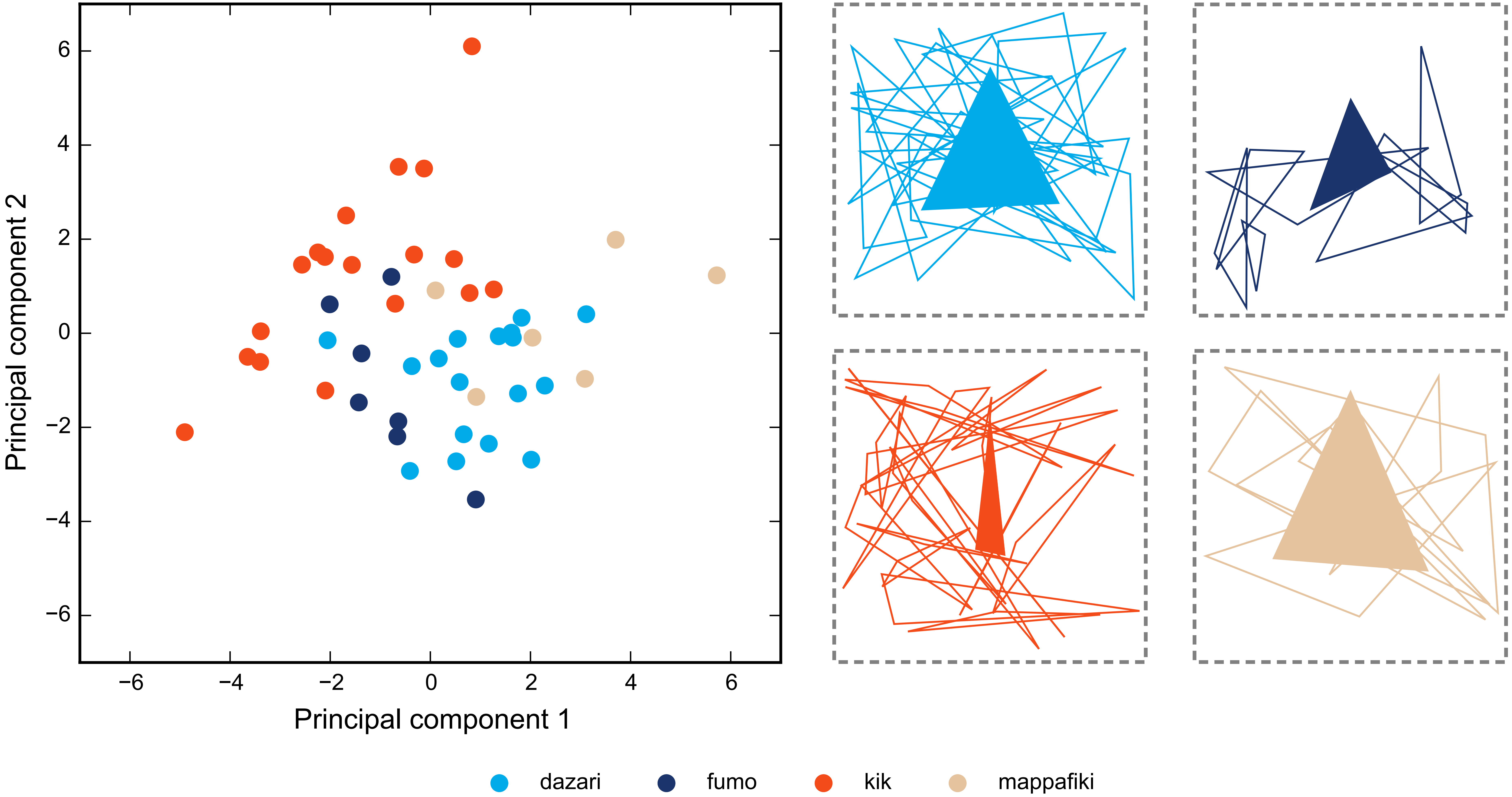


Structure



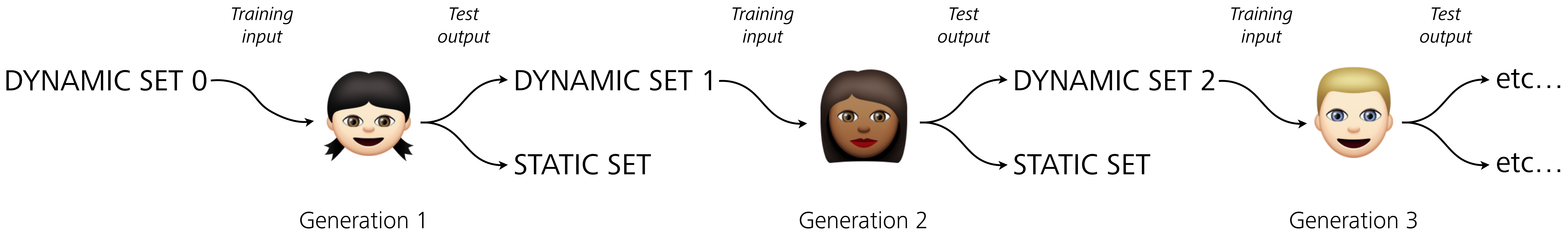
Feature space estimates
Human ratings
Structure (z-score)
14
12
10
8
6
4
2
0
−2
0
1
2
3
4
5
6
7
8
9
10
Generation number
Generation number
Chain A
Chain B
Chain C
Chain D

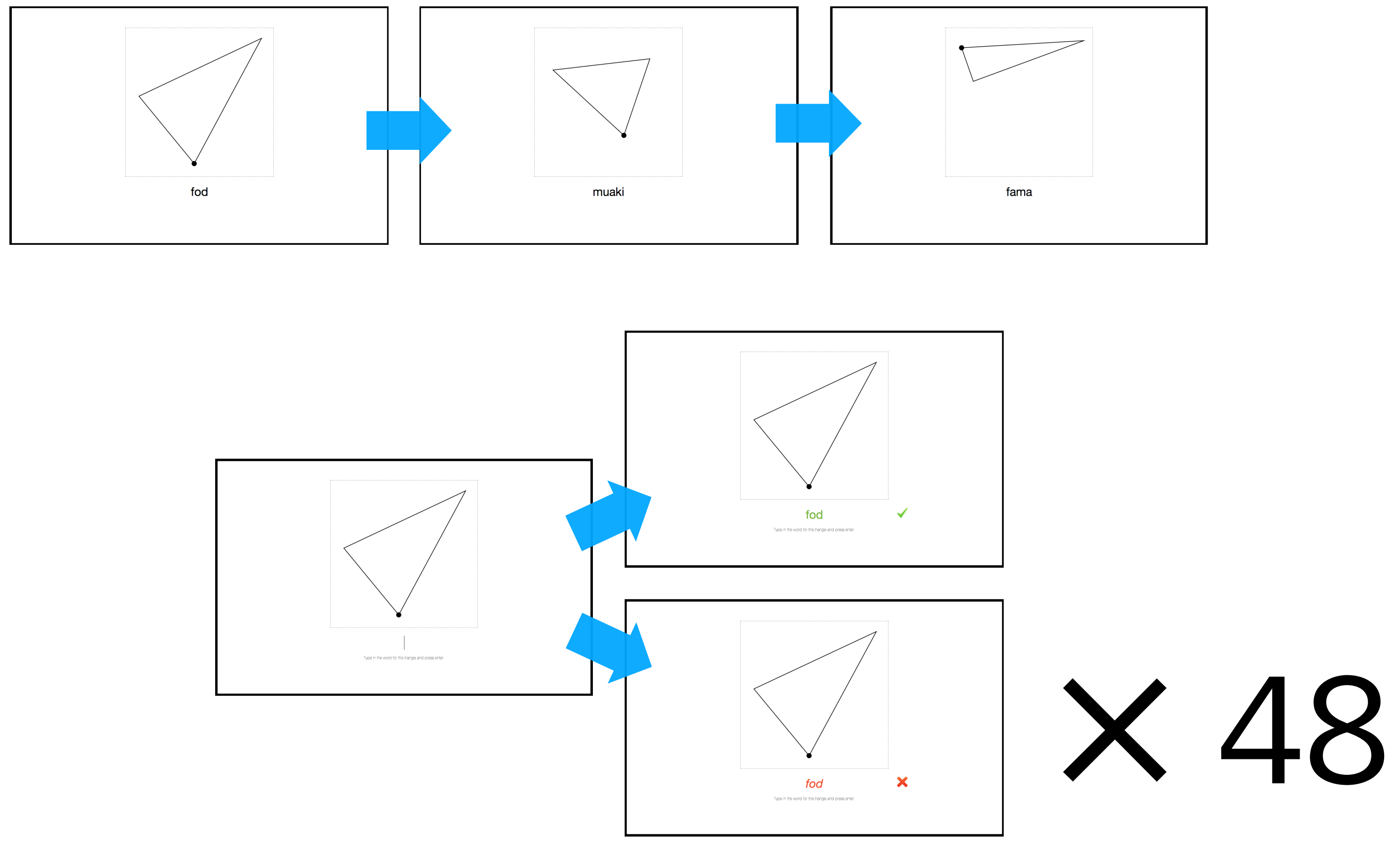
Categorical structure

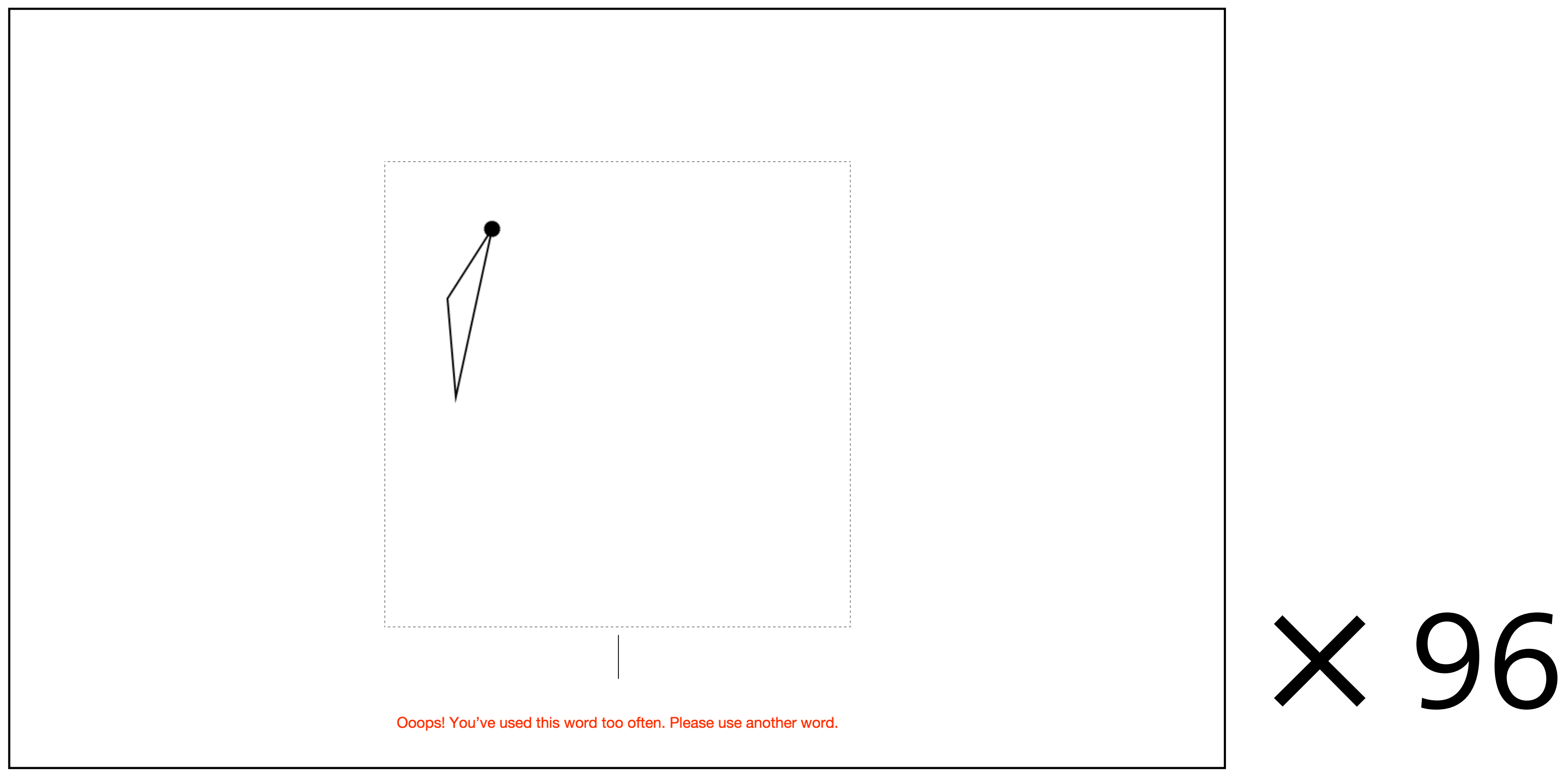


Experiment 2

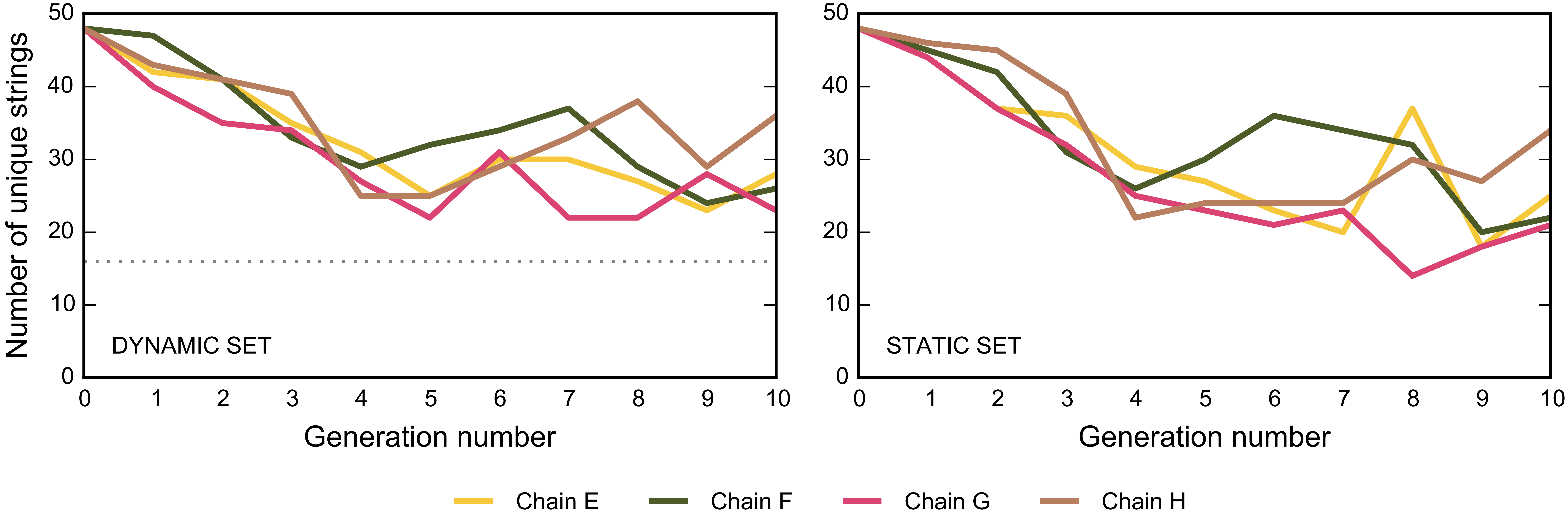
Experiment 2 setup



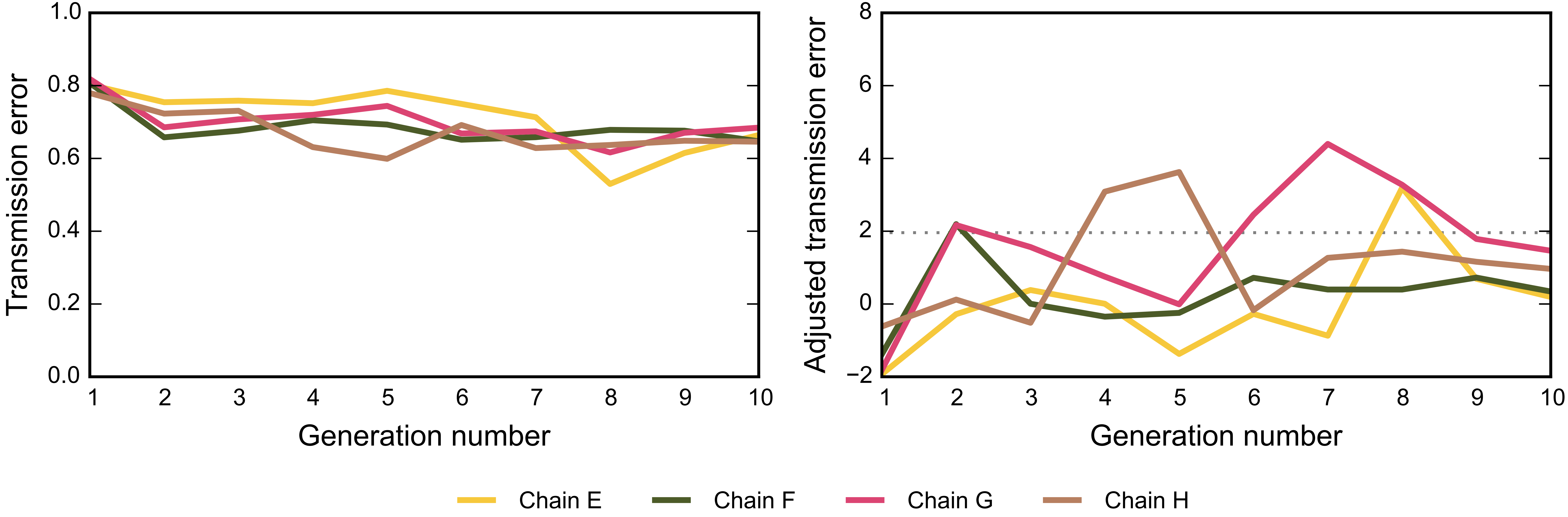




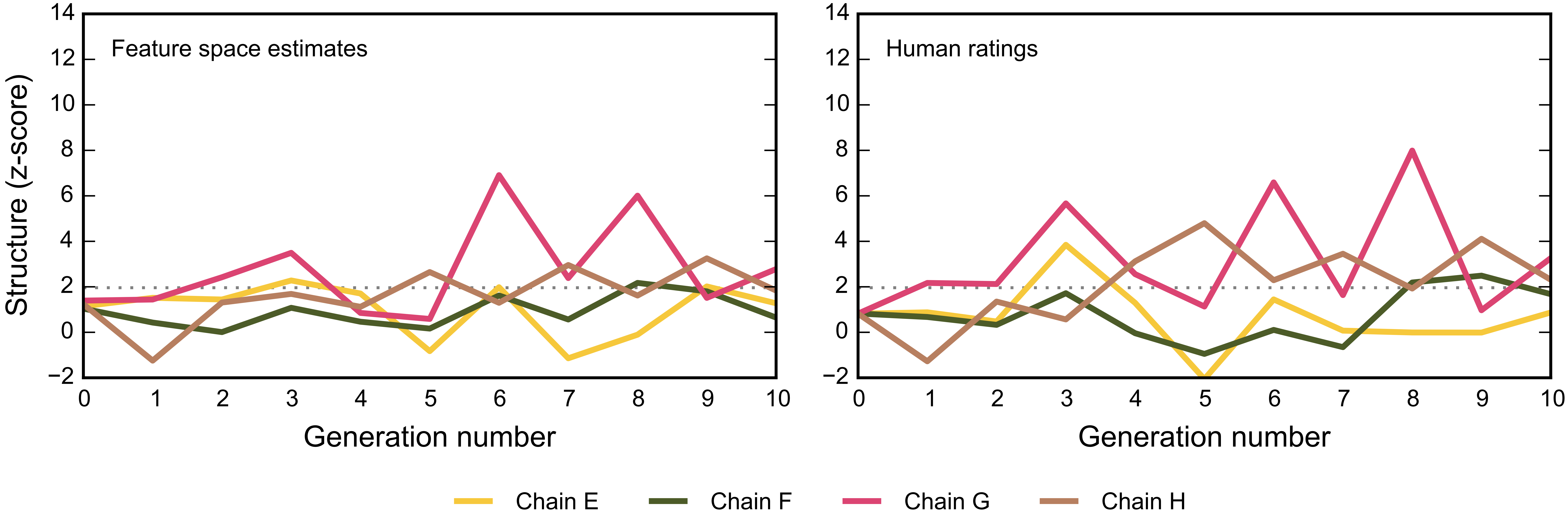
Expressivity



Learnability

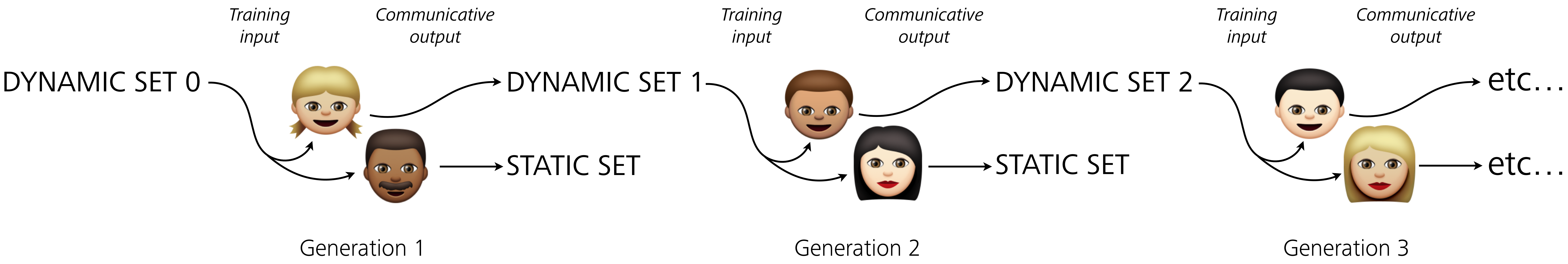


Structure

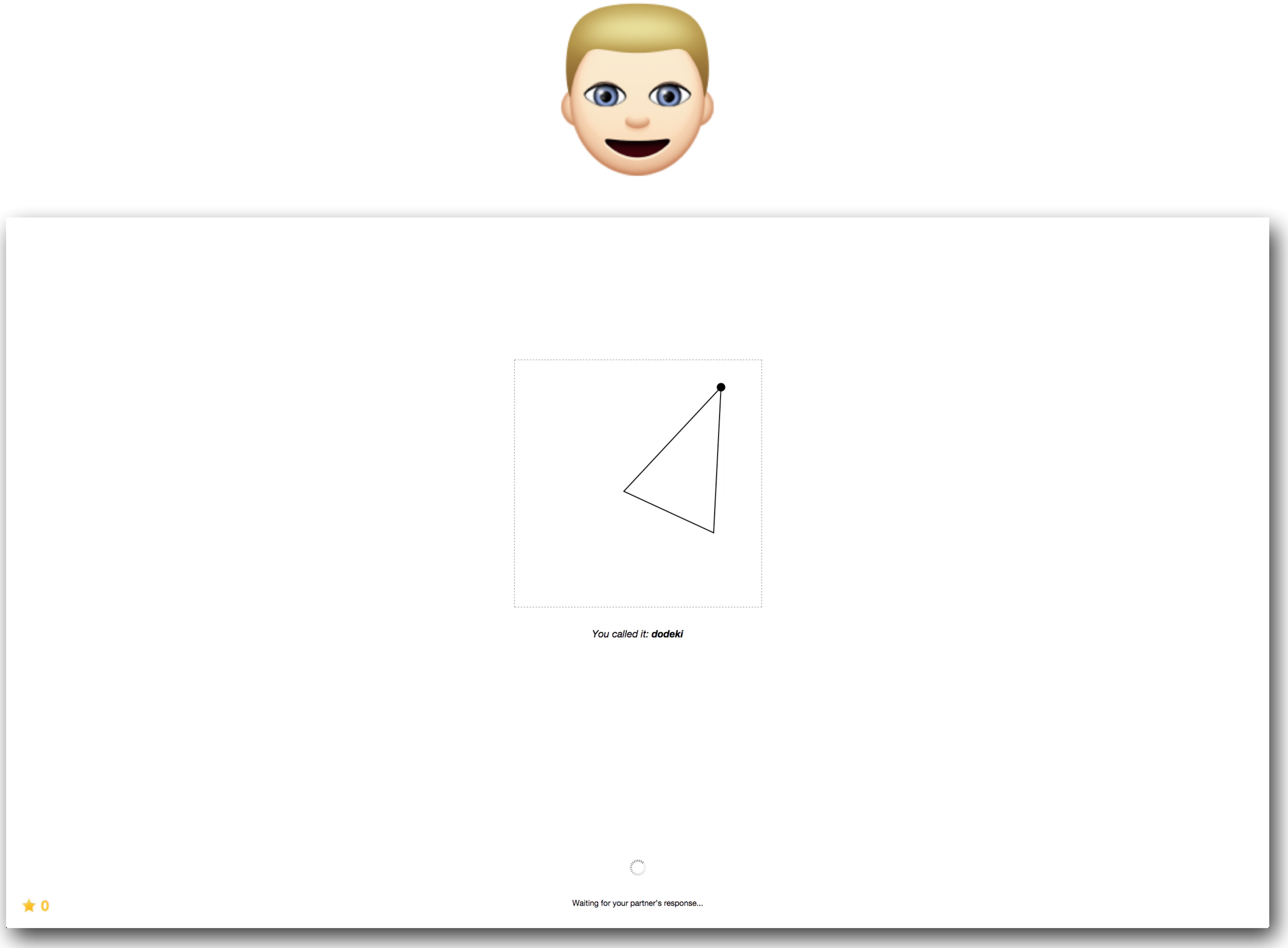

Structure (z-score)
Feature space estimates
Human ratings
14
12
10
8
6
4
2
0
−2
0 1 2 3 4 5 6 7 8 9 10
Generation number
Chain E
Chain F
Chain G
Chain H

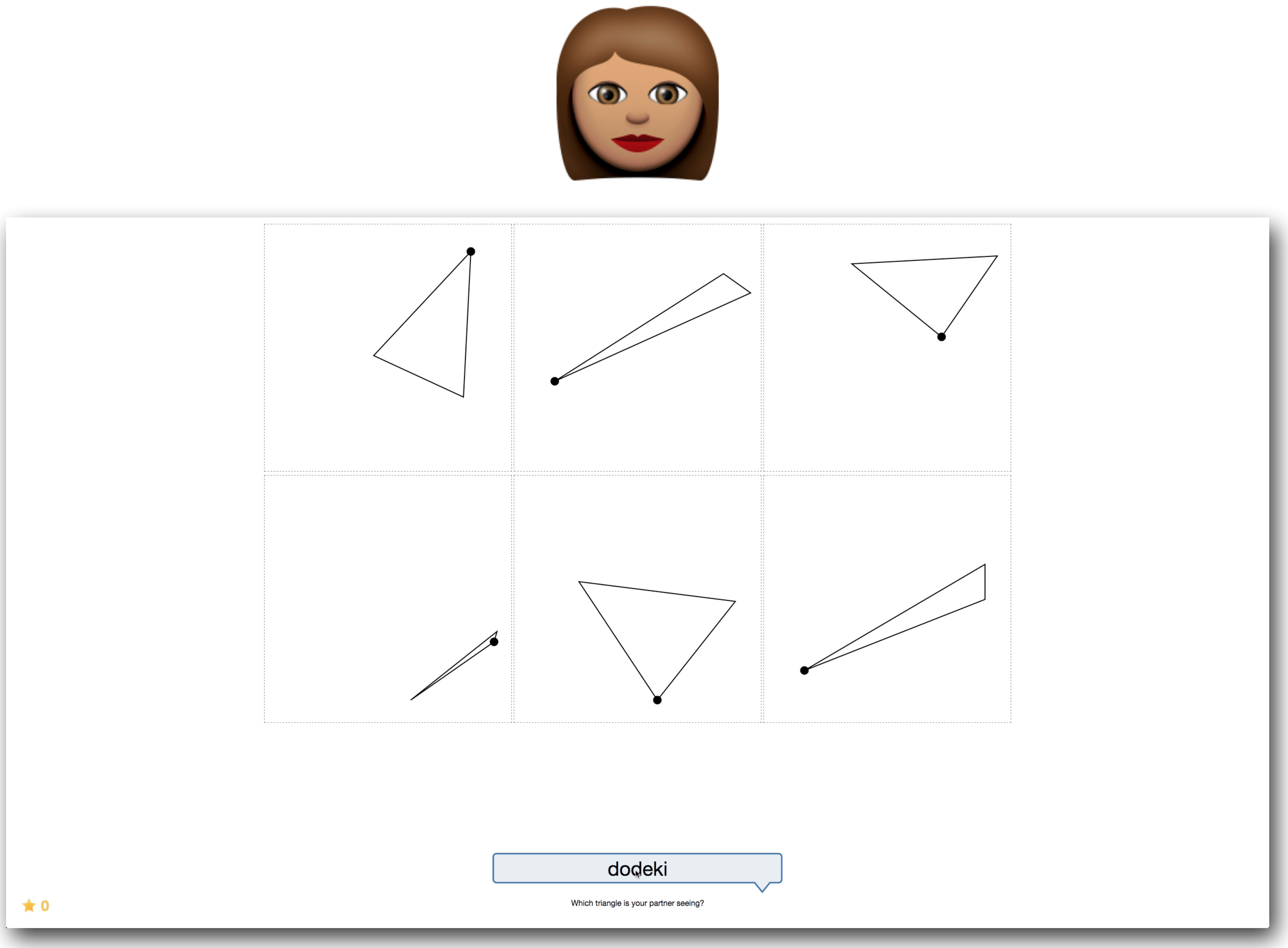
Experiment 3

Experiment 3 setup

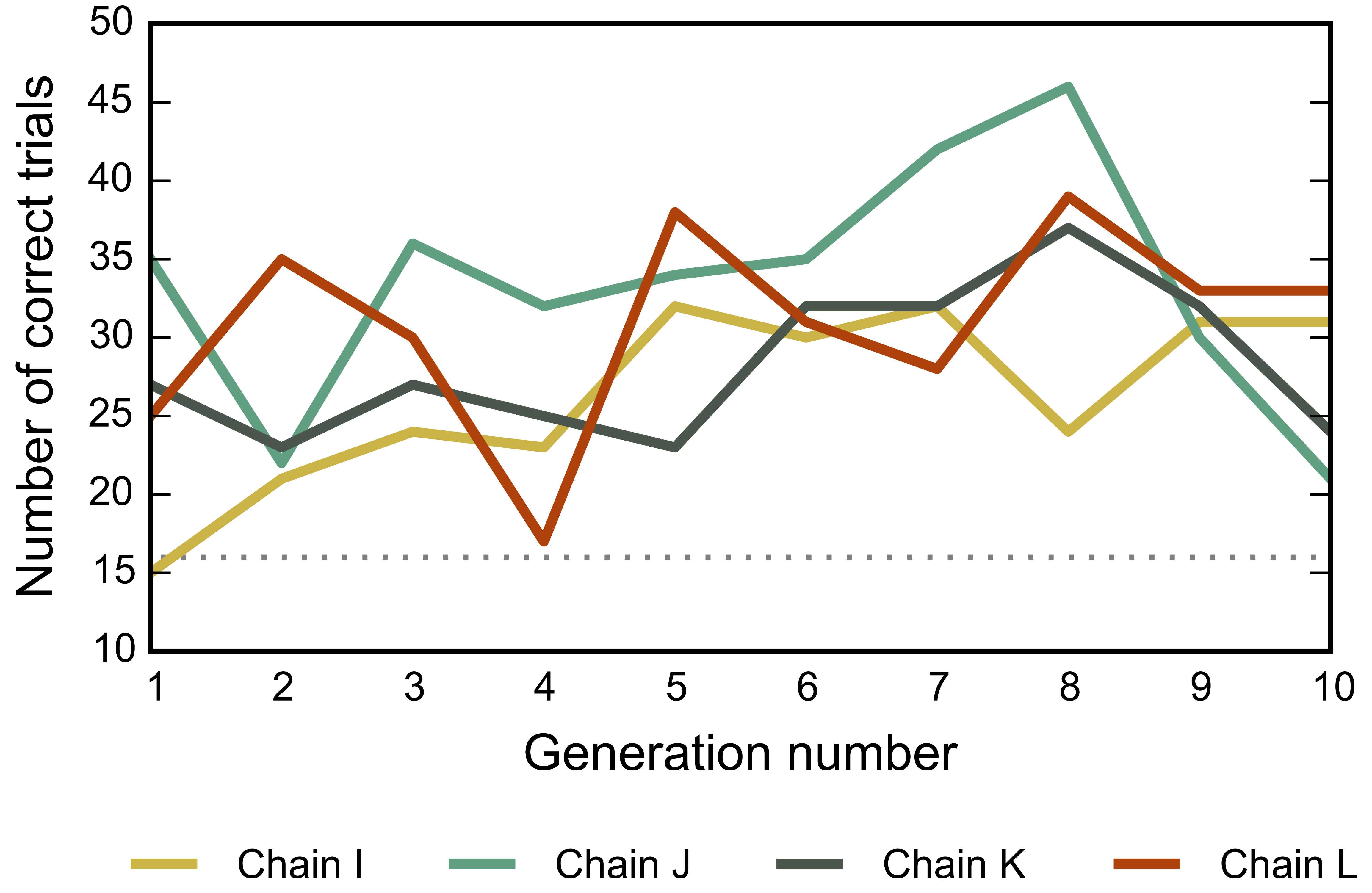


Communication phase

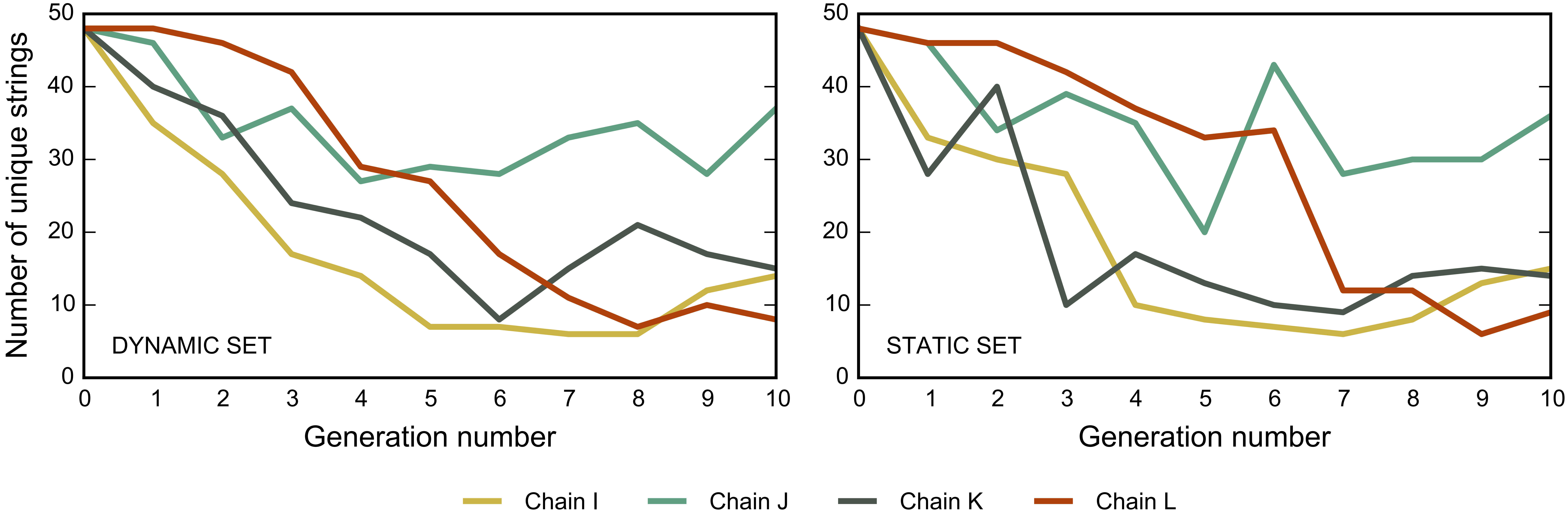




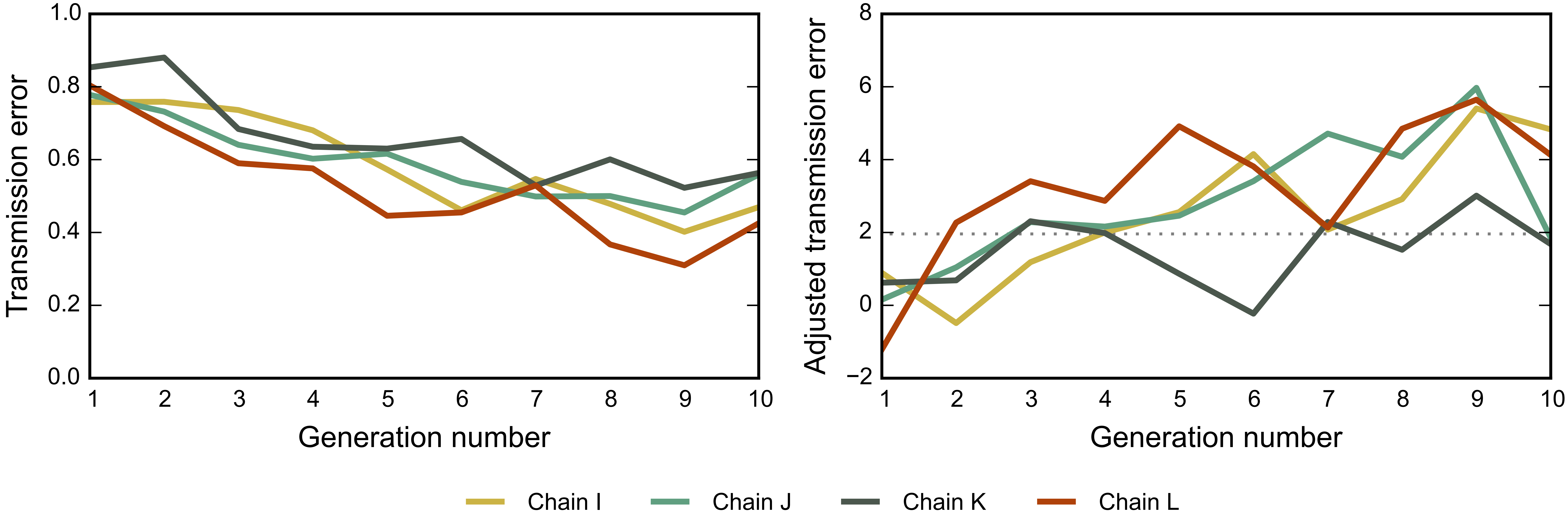
Communicative accuracy



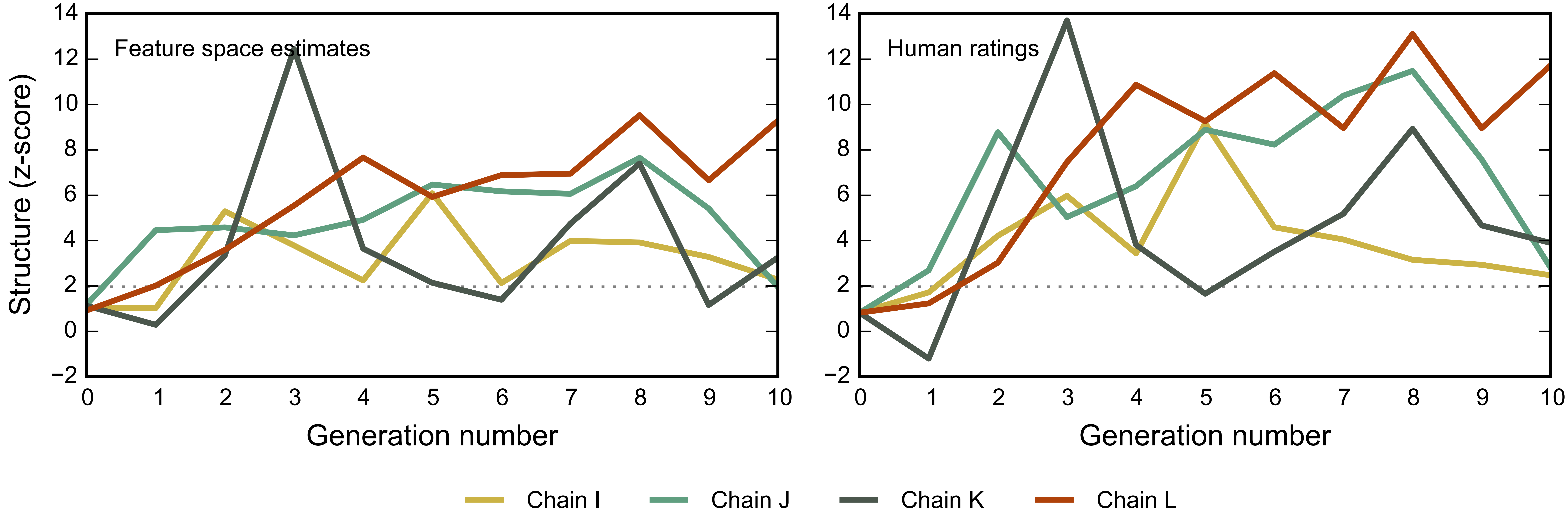
Expressivity



Learnability



Structure



Feature space estimates
Human ratings
Structure (z-score)
14
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10
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6
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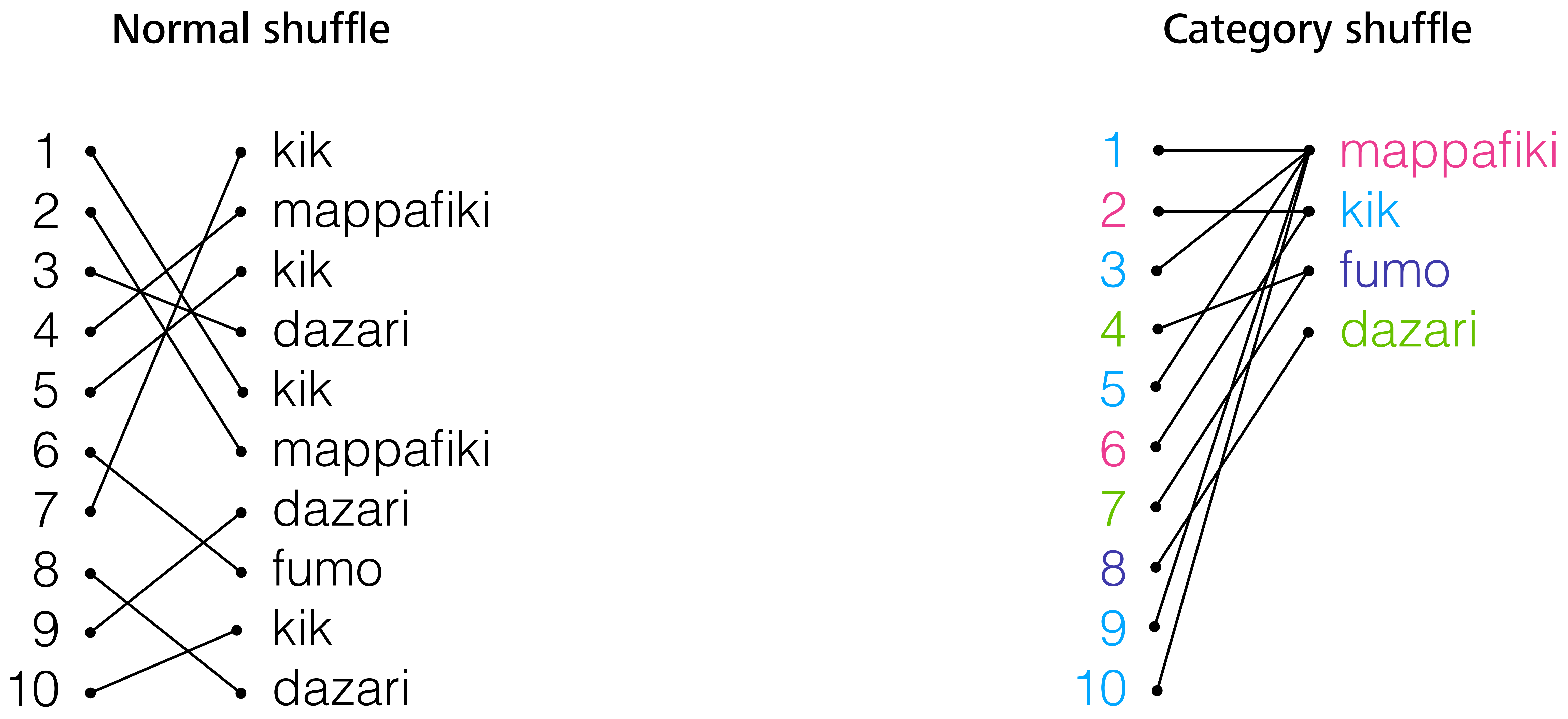
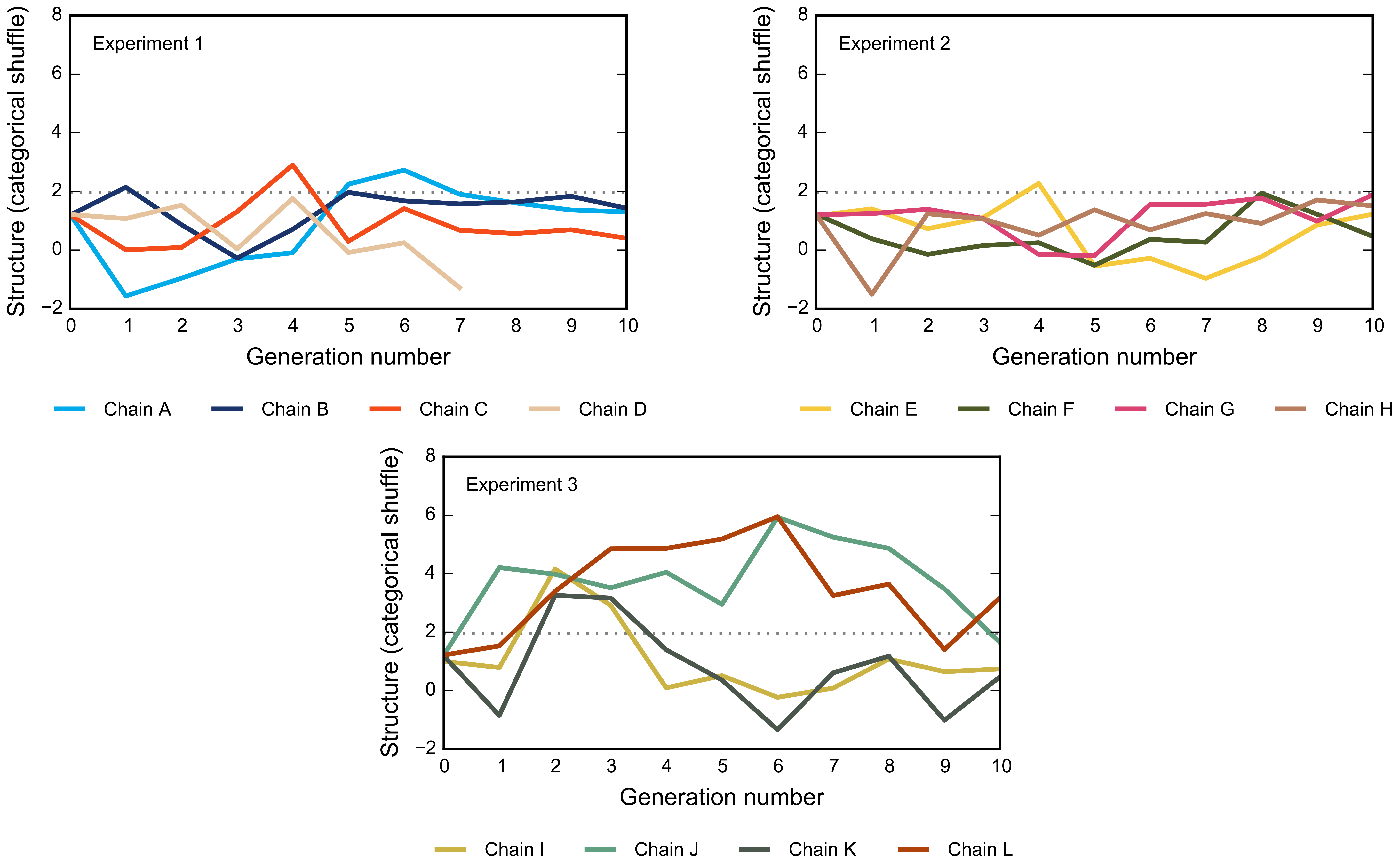
0
−2
0
1
2
3
4
5
6
7
8
9
10
Generation number
Chain I
Chain J
Chain K
Chain L

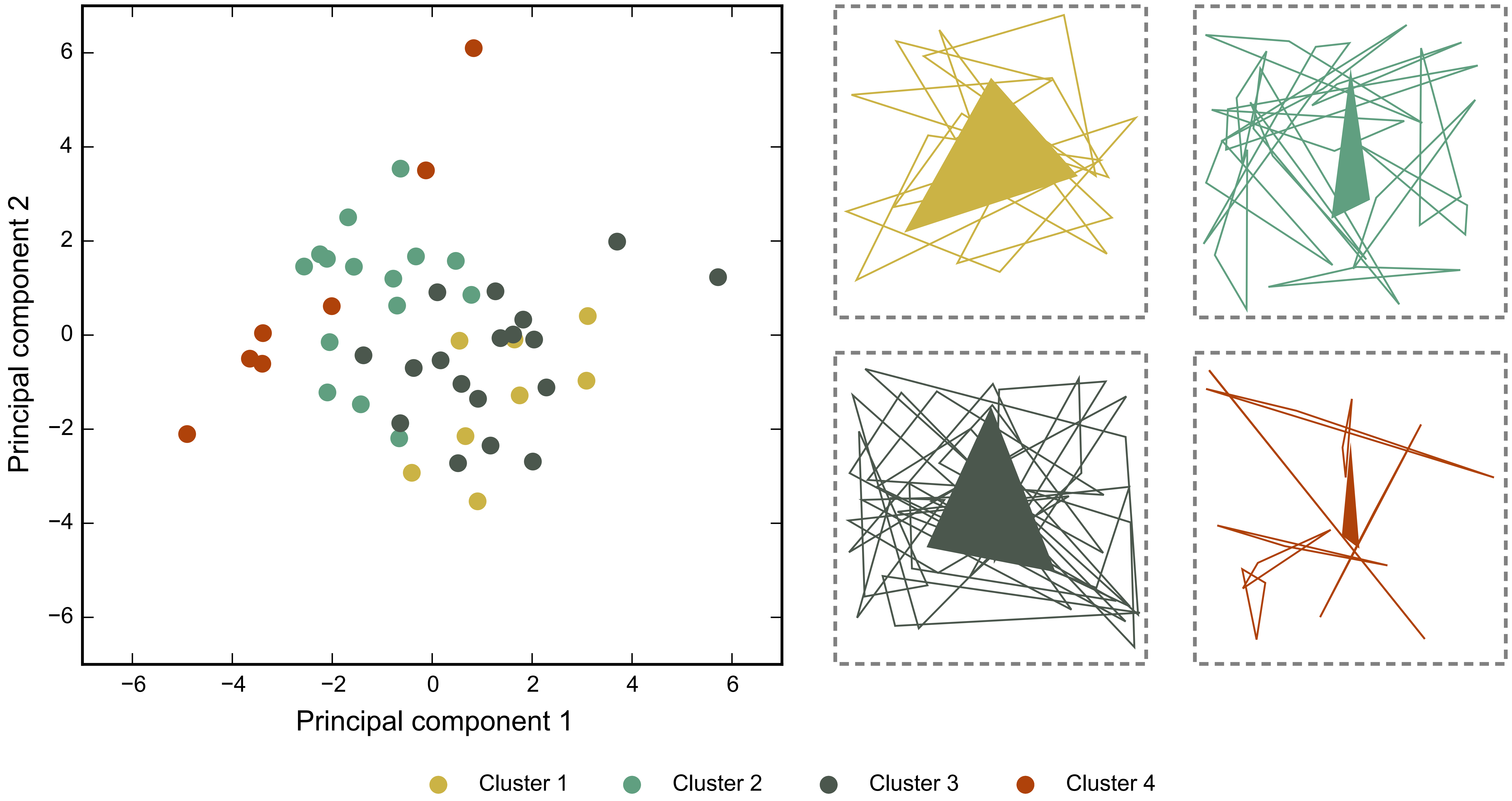
Shuffling methods in the Mantel test



Emergence of *compositional* structure



Categorical structure



Cluster 1 = *fababa*, *badaba*, *bababa*. Cluster 2 = *famapiku*, *mapiku*. Cluster 3 = *madafa*, *mamada*, *mafada*, *famada*, *bafada*. Cluster 4 = *piku*, *pikupiku*.

Conclusions

Conclusions

Experimental method for an “open-ended” meaning space

Iterated learning in simple linear transmission chains gives rise to categorical structure in the meaning space, despite the fact that stimuli never reoccur across participants

Iterated learning with pairs of communicators can give rise to compositional structure in the signal space in addition to the categorical structure in the meaning space

Kirby et al.’s (2008) second experiment is a special case: artificial pressures work when you have a discrete meaning space

Supports a cultural evolutionary account of language evolution


Hannah Cornish


Simon Kirby


Kenny Smith

Thanks!

References

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