COMPOSITIONALITY ARISES FROM ITERATED LEARNING DESPITE A PREFERENCE FOR HOLISTIC SIGNALS: AN EXPERIMENTAL MODEL OF SIGN LANGUAGE EMERGENCE

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Background Cultural evolution has been proposed to account for the origins of compositionality (Smith, 2018), by which we mean the use of a segmented sequence of signal elements, each of which encodes part of the meaning of the whole signal. Often in evolutionary models and experiments, the starting state of a language is assumed to be holistic, lacking sequential segmentation of signals into meaningful sub-parts. Ultimately, a cognitive bias is assumed, which leads to the replacement of a holistic starting state with a compositional one. But if a bias against holistic representations exists, why would they ever arise in the first place?

We use the example of the gradual emergence of segmented manner/path representations in Nicaraguan Sign Language (Senghas, Kita, & Ozyürek, 2004) to investigate whether this kind of segmented compositionality can arise through iterated learning *even if there is an initial preference in favour of non-segmented representations*. We use a series of large-scale experiments (N=1700) in which participants choose between two gestures describing events, specifically videos of balls moving along different paths and in different manners, (Schouwstra, Abramova, Motamedi, Smith, & Kirby, 2014). The gestures either describe the video by encoding manner and path simultaneously, or by segmenting them (e.g. gesturing the path, then the manner).

Experiments In **experiment 1**, participants (N=100) were presented with 16 videos of balls moving with four different paths (e.g., down a slope, around a circle) and four different manners (e.g., bouncing, sliding). Each video was accompanied by two gesture videos representing the movement iconically, with manner and path either segmented or simultaneous. For each of the 16 videos, participants chose which gesture video best conveyed the event. The results show a strong preference for simultaneous gesture ($\beta = 2.30, SE = 0.34, z = 6.83, p < 0.001$), replicating findings from previous silent gesture improvisation experiments (Clay,

Pople, Hood, & Kita, 2014), and co-speech gesture (Senghas et al., 2004).

Next we tested whether this clear preference for simultaneous gesture is replicated in learning. In **experiment 2**, a new set of participants (N=100) went through the same procedure as before except that they were first exposed to 12 training trials in which a sample of the ball videos were presented alongside a gesture video. Half of the training trials appeared with segmented gestures, half with simultaneous ones. In contrast to the preferences without training, we now see a preference for *segmented* gestures $(\beta = -0.82, SE = 0.28, z = -2.97, p = 0.003)$, and a significant difference between experiment 1 and 2, $(\beta = -2.83, SE = 0.29, z = -9.60, p < 0.001)$.

Although this difference between preferences with and without exposure is striking, the preference for segmented gestures after learning is not as strong as the preference for simultaneous gestures without learning. In NSL, the use of segmentation increases over cohorts, suggesting accumulation through cultural evolution. In **experiment 3**, we ran 100 iterated learning chains using the learning paradigm from experiment 2 in which the participants' choices at generation g is the training data for participants at generation $g + 1$, using the data from experiment 2 as the first generation and continuing for a further 7 generations (N=700). We find that the preference for segmented gestures is amplified over generations $(\beta = -0.10, SE = 0.05, z = -2.36, p = 0.02)$.

These results are compelling evidence that iterated learning can lead to languages that reflect biases that are the *opposite* of preferences of participants prior to learning. However, to fully model the sign language emergence context, where segmented forms emerge following an initial preference for holistic structures, in **experiment 4** (N=800) we replicated experiment 3 using the output of the baseline preference from experiment 1 as seed rather than the 50:50 exposure of experiment 2. Here too we see a significant accumulation of segmented gestures over generations $(\beta = -0.17, SE = 0.05, z = -3.68, p < 0.001)$.

Discussion We can treat language evolution as a Markov process and use all the data from experiments 2, 3 and 4 to estimate the full transition matrix from language to language. From this we derive the stationary distribution for languages. This shows a preponderance of segmented languages, but with some probability mass on simultaneous ones, suggesting that although cultural evolution will tend to lead languages towards segmented compositionality, some variability can nevertheless be expected across sign languages.

These results demonstrate that cultural evolution through iterated learning can lead to outcomes that appear to run counter to preferences prior to iterated learning. We use this to introduce a crucial distinction between *naturalness biases* which affect signals that are not part of a set of conventions, and *systematicity biases* that arise when signals are learned as part of a larger set.

References

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