A Bayesian meta-analysis of naturalness bias in phonological learning

Canaan Breiss (cbreiss@uchicago.edu)[1], Anna Runova [2]
[1]Department of Linguistics, University of Chicago, [2]Department of Linguistics, University of Southern California

Background: Inductive biases contribute to language acquisition and possibly typological asymmetries [1]. In phonological learning, the preference for patterns such as vowel harmony, which may reflect phonetic naturalness, is known as *naturalness bias*. [2, 3]). Artificial Grammar Learning (AGL) experiments are a common approach to testing if patterns deemed more "natural" typologically are also more learnable. Participants learn a miniature language containing the desired phonological properties in the training input and then generalize the learned patterns to novel items at test. Despite decades of work using this methodology, it remains difficult to draw large-scale firm conclusions from this literature (cf. [4, 5, 6]), due to differences in the definition of the term "naturalness", diverse experimental methodologies, and small sample sizes. We conducted the first meta-analysis of AGL experiments on naturalness bias, providing quantitatively unified insights (cf. [7, 8]).
Methods: Following PRISMA [9], we screened publications for inclusion criteria and extracted study characteristics and statistical results, for a total of 44 papers, 82 experiments, 3,572 participants, and 227 effect sizes. We analyzed standardized effect size (Hedge's *g*) with a Bayesian mixed-effects meta-analytic regression model [10]. **Results:** Patterns identified as "natural" by study authors have a larger effect size than "unnatural" patterns, reflecting better learning (Fig. 1). Delving into different operationalizations of "natural", though, we find only patterns with phonetic precursors show a learnability advantage, with no role for typological prevalence or number of sound changes involved. Moreover, we found suggestive evidence that perceptually-based phonetic precursors are more advantaged than articulatorily-based ones (Fig. 5), in line with prior work [4, 5]. We also found that almost all studies used auditory stimulus presentation and did not include a production component; thus it is likely that any modality-specific advantage is confounded with experimental task. Methodologically, we find that there is no evidence that online experiments differ meaningfully in effect size from those carried out in-lab, supporting the validity of this increasingly-common design choice. We also found that overall, the studies in our meta-analysis have only 20% post-hoc power (Fig. 3), and show evidence of publication bias (Fig. 4). Going forward, we recommend the following best-practices: high-powered (>70 subjects/cell), preregistered studies, with clear operationalizations of core constructs of interest (ex. "naturalness"), and varied modality (ex., speech production, perception.)

Fig. 1: Overall effect of naturalness

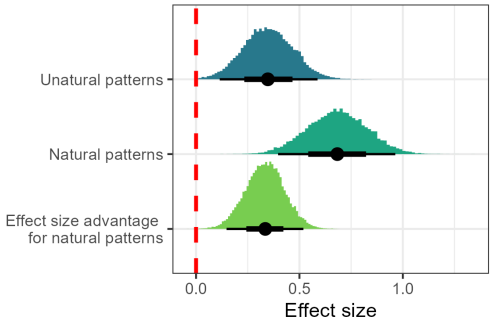


Fig. 2: Moderators

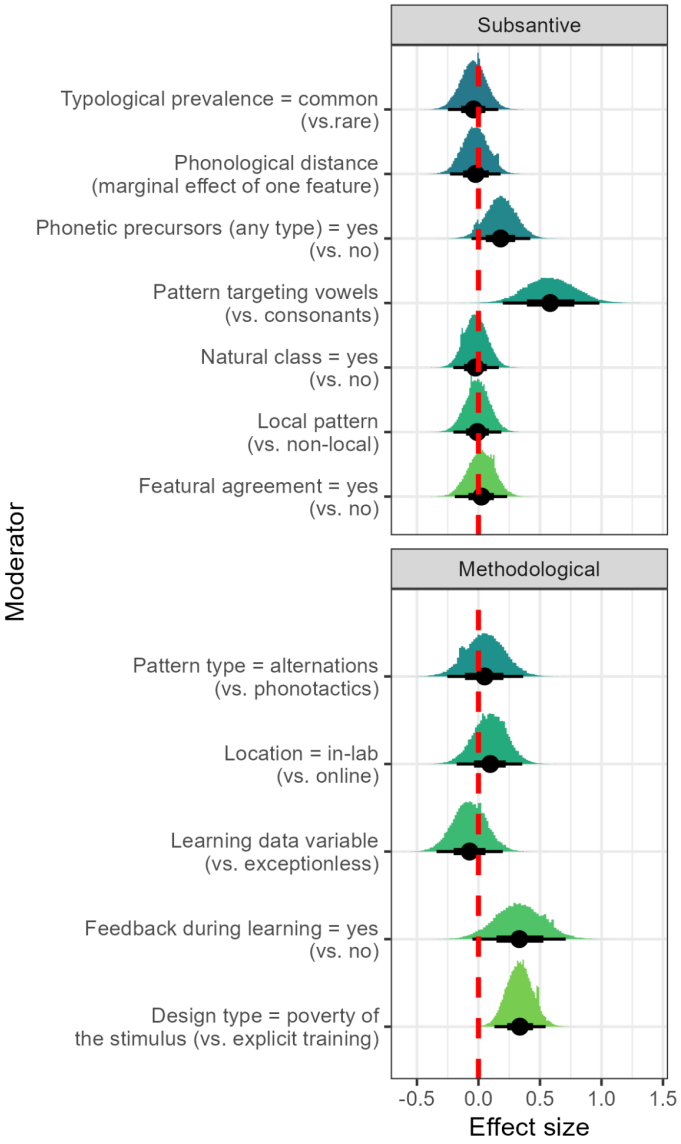


Fig. 3: Distribution of post-hoc power

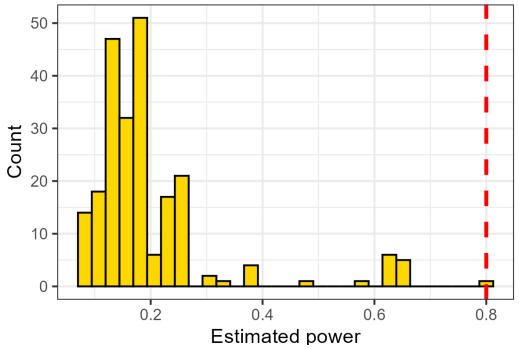
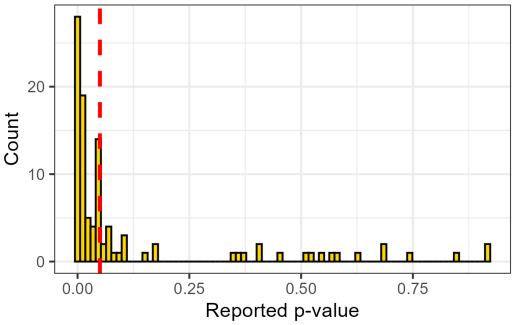


Fig. 4: Distribution of reported p-values



References: [1] Chomsky 1965. Aspects of of syntax. MIT Press. [2] Moreton, E., & Pater, J. (2012a). Structure and Substance in Artificial-phonology Learning, Part I: Structure. Language and Linguistics Compass, 6(11), 686–701 [3] Moreton, E., & Pater, J. (2012b). Structure and Substance in Artificial-Phonology Learning, Part II: Substance. Language and Linguistics Compass, 6(11), 702–718. [4] Glewwe, E. R. (2019). Bias in phonotactic learning: Experimental studies of phonotactic implicationals. [5] Do, Y., & Havenhill, J. I. "Production and substantive bias in phonological learning." Proceedings of the Annual Meetings on Phonology. Vol. 8. 2021. [6] Zheng, S., & Do, Y. (2025). Substantive Bias in Artificial Phonology Learning. *Language and Linguistics Compass*, *19*(1) [6] Kiparsky, P. 1965. *Phonological Change*. [7] White, J.. "Evidence for a learning bias against saltatory phonological alternations." *Cognition* 130.1 (2014): 96-115. [9] Page M J, McKenzie J E, Bossuyt P M, Boutron I, Hoffmann T C, Mulrow C D et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews BMJ 2021; 372 [10] Stan Dev. Team, 2025 Stan Reference Manual, v. 2.36.

Fig. 5: Phonetic precursor type

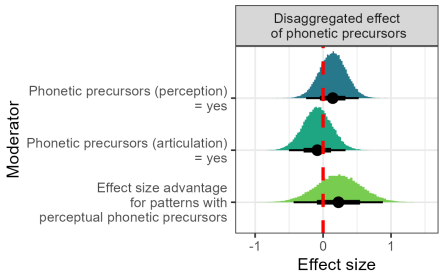


Table 1

Overall effect	Median and 95% CI	P-direction
Natural	0.68 [0.40, 0.96]	1
Unnatural	0.35 [0.11, 0.35]	1
Advantage for natural	0.33 [0.15, 0.52]	1
Moderator		
Typological prevalence	-0.04 [-0.25, 0.16]	0.65
Phonological distance	-0.01 [-0.2, 0.19]	0.54
Phonetic precursors (any type)	0.18 [-0.05, 0.42]	0.92
Pattern targeting vowels	0.34 [0.13, 0.55]	1
Natural class = yes	-0.02 [-0.2, 0.17]	0.6
Featural agreement = yes	0.02 [-0.2, 0.23]	0.59
Pattern type = alternations	0.05 [-0.25, 0.37]	0.62
Location = in-lab	0.1 [-0.18, 0.36]	0.76
Learning data variable	-0.07 [-0.35, 0.19]	0.69
Feedback during learning = yes	0.33 [-0.05, 0.71]	0.96
Design type = poverty	0.33 [0.13, 0.55]	1