Diversity and universals in culturally evolved sound systems across species: A complex adaptive system account

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Diversity and universals are concurrent features in culturally evolved sound systems (Oudeyer, 2005). Diversity, as evidenced by cross-linguistic differences (Evans & Levinson, 2009), contrasts with universals, which here denote consistent statistical tendencies across languages (Bybee, 2010). For example, while vowel inventories vary significantly among languages (Maddieson, 1984), three prevalent vowels are consistently observed in the majority of languages (Schwartz, Boë, Vallée & Abry, 1997). Similarly, in cetacean vocal systems shaped by cultural transmission, although dialectal diversity exists in killer whale calls (Filatova et al., 2012) and sperm whale codas (Weilgart & Whitehead, 1997), certain calls in killer whales (Rehn, Filatova, Durban & Foote, 2011) and hierarchical structures in humpback whale songs (Payne & Payne, 1985) suggest universality, implying a potential convergent mechanism across species for sound system distribution and change in cultural evolution.

Research attempts to elucidate the origins of diversity and universals. The *Acoustic Adaptation Hypothesis* (Wiley & Richards, 1978), originally formulated in animal communications, extends to human spoken language (Maddieson & Coupé, 2015), highlighting diversity in adaptation to different ecological environments. Conversely, universals arise from cross-linguistic communicative tradeoffs (Coupé, Oh, Dediu & Pellegrino, 2019). Information per syllable and speech rate differ across languages, however, encodings for each language are largely balanced, efficient, and universal. Similar viewpoints have been proposed in other domains of language. The *Linguistic Niche Hypothesis* (Lupyan & Dale, 2016) emphasizes that morphological complexity reflects the structural complexity of speech communities, adapting to various social environments. Similarly, the *Efficient Communication Framework*

(Kemp, Xu & Regier, 2018) underscores the necessity for languages to balance informativeness (e.g., kinship terms of reference) and cognitive load (e.g., number of such terms) for high communicative efficiency.

This article aims to integrate these theories within a *complex adaptive systems* (CAS) account by comparing existing *agent-based models* (ABMs) of human vowel systems and cetacean vocal systems. These simulations explore evolutionary dynamics in CAS by simulating global changes through local interactions among artificial agents with cognitive capabilities (Holland, 2000).

De Boer's *Imitation Game* (2000) demonstrates how vowel universals can emerge through local interactions among agents without presupposing innate constraints. How adaptation leads to diversity was also investigated in some extensions of the model. De Boer and Vogt (1999) demonstrated that differences in social structures and demographics collectively shape vowel systems. Chirkova and Gong (2014) showed that when a new vowel entered into a vowel system, the original vowel distribution could dynamically adapt and readjust to maintain contrast with the original vowels and the newly-entered one, thus forming a novel vowel system.

It is generally accepted that cetacean vocalisation is learnt rather than transmitted genetically (Whitehead & Rendell, 2014). Research on cetacean vocalization suggests that dialectal diversity arises from female-centric social learning mechanisms and multilevel societies (Filatova & Miller, 2015; Cantor et al., 2015). The ABMs of humpback whale songs focused on factors that influence evolution patterns, such as migration and population contact (Mcloughlin et al., 2018). Although no model has explored which innate constraints shape the universal song form, research shows that similar learning parameters lead to different evolutionary patterns of the song for a universal goal (Zandberg, Lachlan, Lamoni & Garland, 2021).

These ABMs illustrate sound system evolution as a process of self-adaptive optimization. Diversity arises from differences in adaptation strategies across environments, while universals stem from common conditional constraints and specific goals (e.g., communicative for humans and biological for non-human animals, Steels, 2017). It can uncover generalizable principles underlying the emergence of diversity and universals in language evolution by comparing ABMs of sound systems. Such cross-species comparisons offer insights into the social-cognitive mechanisms driving language evolution and the perpetuation of endless change (Steels, 2017). Moreover, similar issues of diversity and universals exist in other aspects of human languages (e.g., color terms, Gong et al., 2019), suggesting that these principles may extend beyond sound systems.

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