Explore-exploit trade-off in vocal learning

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Introduction: Early vocalizations tend to be noisy and less structured in vocal learners such as humans and songbirds. This variability has been suggested to be part of the process of motor exploration, facilitating the learning process [1]. Yet, studies of vocal learning emphasize imitation, a process in which the human or songbird is assumed to copy the vocalization produced by its tutor, in most cases excluding motor exploration from the definition of vocal learning [2]. This elicits the question of whether exploration is necessary for vocal learning and whether exploitation of what they've learned through external stimuli and rewards is sufficient.

Method: We used empirical data and built a reinforcement learning (RL) agent with biomechanical constraints to study the question. The RL model allows us to control the amount of exploration versus exploitation processes. The RL environment is based on a biomechanical model of the vocal apparatus in which actions are parameters for this model (air pressure in the lungs and vocal fold tension). The rewards are how closely the agent managed to reproduce a heard vocalization. We also keep track of the errors as the opposite of the rewards.

Results: If exploration is relevant, we expect the acoustic variability to be higher at the beginning of vocal learning. To test this, we determined whether variability in vocal acoustics was present in the early developmental periods of three species that exhibit vocal learning: humans, songbirds, and marmosets. Despite the different learning mechanisms that the three species go through, they all show a high degree of variability within their initial vocalizations compared to the later ones (Fig 1**A**). Next, we investigate, using an RL agent, whether starting the learning process with exploration brings any advantage compared to when only imitation is present (Fig 1**B**). To do that, we evaluate an RL model in which we can control the amount of exploration versus exploitation. The exploration model led to more accurate (smaller training error) and more robust (smaller error for unseen calls) learning by the end (Fig 1**C**).

Discussion: Our result suggests that exploration is present in the early developmental stages of vocal learners and might facilitate the vocal learning process by allowing robust learning of new vocalizations. Our model also suggests that exploration can solve the problem of "poverty of stimulus", in which the external stimuli are insufficient to explain the richness in the vocalization. By exploring its own vocal space, vocal learners create acoustic richness without external stimuli.

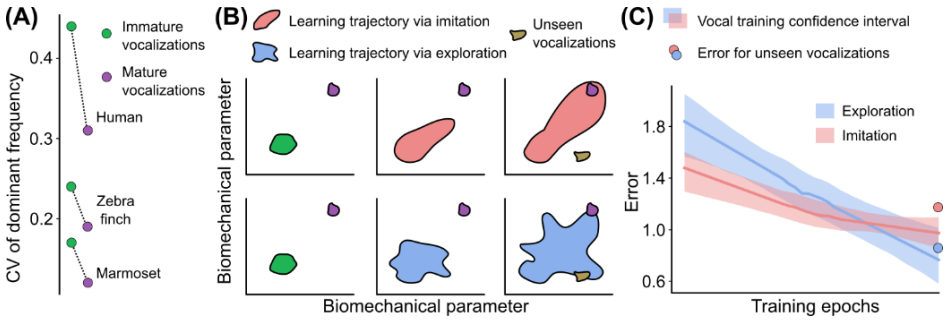

Figure 1. (A) Immature vocalizations have higher variability than mature vocalizations in vocal learning animals. This is shown here through the coefficient of variation of the dominant frequency of vocalizations emitted by humans (CHILDES: Cruz-Ferreira, M., 2003, and Brent et al., 2001), zebra finches (Tchernichovski et al., 2001), and marmosets monkeys (Takahashi et al., 2015). **(B) Schematics of the space of biomechanical parameters and learned vocalizations over time**, from left (immature) to right (mature). Purple spot represents the target vocalization being learned. Top panels represent learning via imitation, while bottom panels represent learning via exploration. **(C) Exploration mechanism learns faster and is more robust.** The result can be seen via the training curves (lines) for 40 epochs, and performance on unseen data (dots) after training, for RL agents that learned with low exploration (red, eps-greedy policy with eps = 0.1) and with high exploration (blue, eps-greedy policy with eps = 0.9) parameters.

References: [1] Lipkind D., Geambasu A., Levelt C.C., Top. Cogn. Sci. **12** (2019) 894-909; [2] Fischer J., Hammerschmidt K., Phil. Trans. R. Soc. B **375** (2020).