Reward-based learning of sensorimotor synchronization in recurrent neural networks

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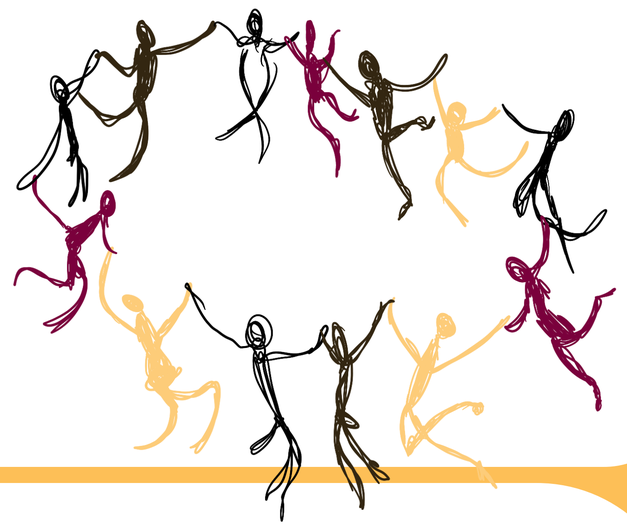
Introduction



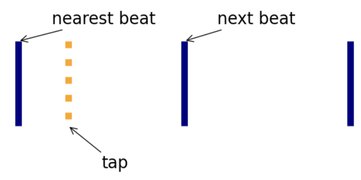
- **Sensorimotor Synchronization (SMS):**
  - The ability to **coordinate movements with external rhythmic stimuli** (e.g., tapping to a beat).
  - Essential in activities such as music performance, speech, and social interactions.
  - Humans naturally **develop** synchronization skills over time, but not animals.
  - **Learning** plays an important role in synchronization, e.g. **musical training** and **cultural exposure.**
- **Objective of Study:**
  - How can SMS be learned?

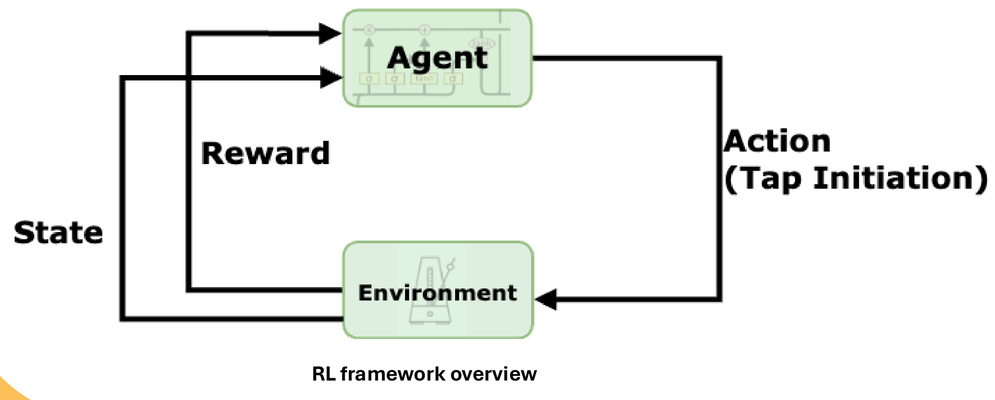
Teaching Monkeys to Synchronize

- Unlike humans, monkeys do not naturally synchronize but can **learn** to tap in time with rhythmic stimuli **when rewarded**.
- **Betancourt et al.** successfully trained monkeys in a SCT task, using juice rewards responding to both tap asynchrony and inter-tap intervals.
- **Takeya et al.** showed that monkeys can learn **predictive synchronization** to visual metronomes when rewarded immediately, generalizing this ability to untrained tempos.
- These findings suggest **synchronization can be learned through reinforcement** in non-human primates.

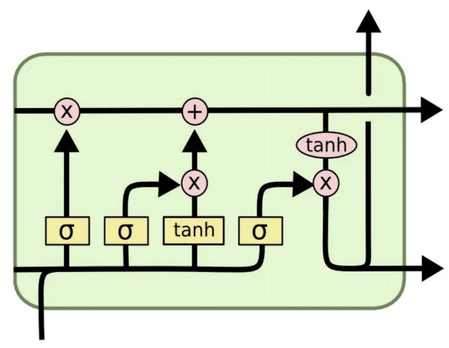
Methodology

- Trained a recurrent neural network to synchronize using rewards, inspired by monkey training
- **Agent**: recurrent neural network **(RNN)** with **(LSTM)** units
  - **Input**: "clicks" (auditory cues)
  - **Output**: "taps" initiation (motor actions)
  - **Reward**: key reward structures:
    - **Asynchrony Minimization:** Asynchrony regarding the ***NEXT*** or ***NEAREST*** beats
    - **Interval Accuracy:** Rewards were given for maintaining consistent time intervals between taps





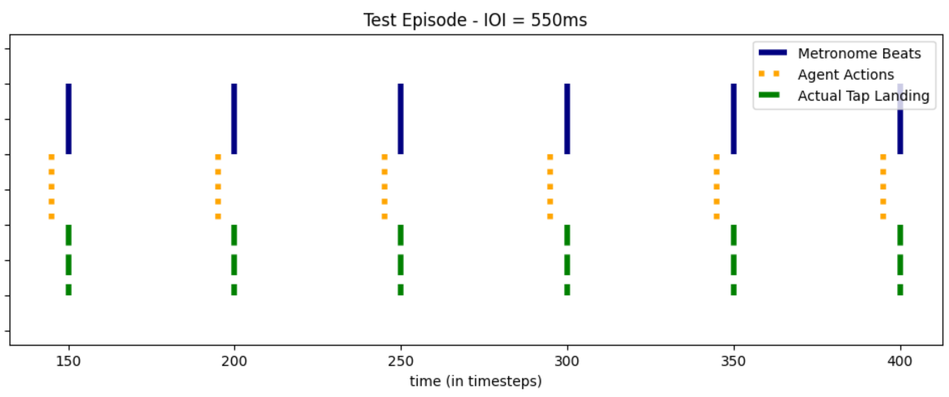
RL framework overview



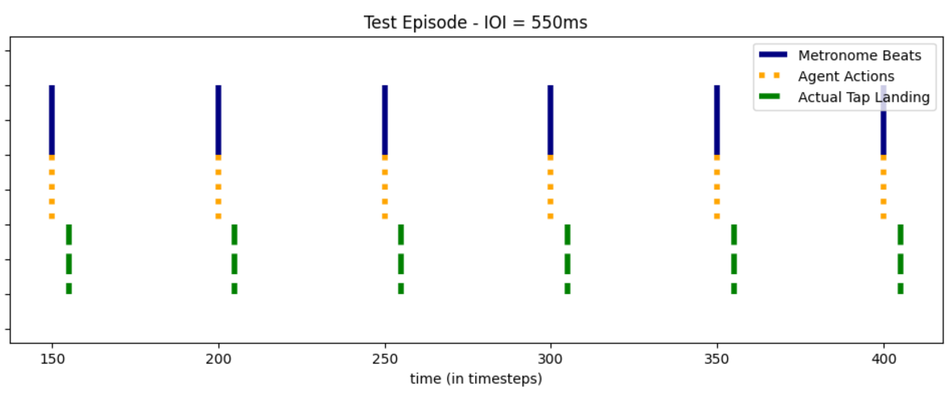
An LSTM unit

Results

Metronome Synchronization:



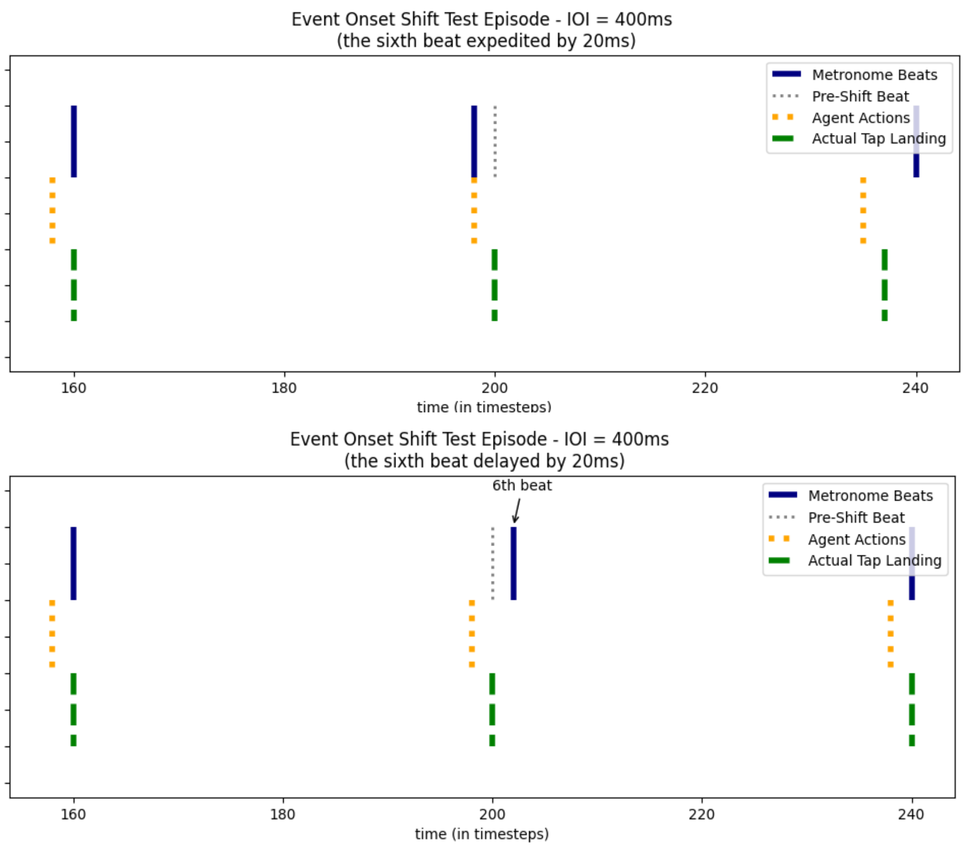
Agents trained with a combination of **next-beat asynchrony minimization and interval accuracy rewards** exhibited human-like SMS behaviors.

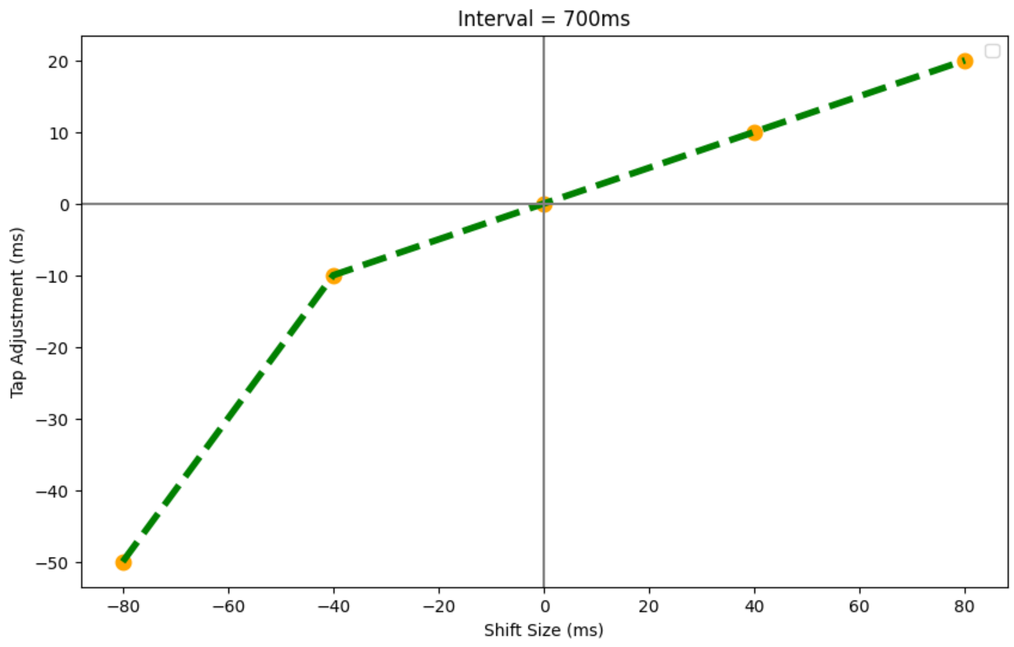


Agents trained with **nearest-beat asynchrony** settled on a **reactive** strategy.

Event Onset Shift:

- Agents trained with both next-beat asynchrony and interval rewards showed **asymmetric error correction**, where larger adjustments were made after tapping late than after tapping early.





Asymmetric Error Correction

- With a **noisy input**, asymmetric error correction leads to negative mean asynchrony (anticipatory tapping), as shown in **Tomyta et al.**

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References

- **Betancourt, Abraham, et al.** Amodal population clock in the primate medial premotor system for rhythmic tapping. *Cell Reports* 42.10 (2023).
- **Takeya, Ryuji, et al.** Predictive and tempo-flexible synchronization to a visual metronome in monkeys. *Scientific reports* 7.1 (2017): 6127.
- **Tomyta, Kenta, Hideki Ohira & Kentaro Katahira.** Asymmetric Error Correction in the Synchronization Tapping Task. *Timing & Time Perception* (2023):

Conclusions

- **Learned Synchronization:** Synchronization can be learned in neural networks using reward schemes similar to those used on monkeys.
- **Reward-Driven Learning:** Reward structure shapes acquired strategy: Reactive vs. Anticipatory.
- **Better-Early-Than-Late:** The fact that the *next-beat* agents learn better, indicate that humans may naturally favor early actions.
- **Asymmetric Error Correction** may arise from the intrinsic reward system that most effectively trains synchronization: rewarding early taps more than late taps.