Rats trade initial rewards for long-term learning opportunities

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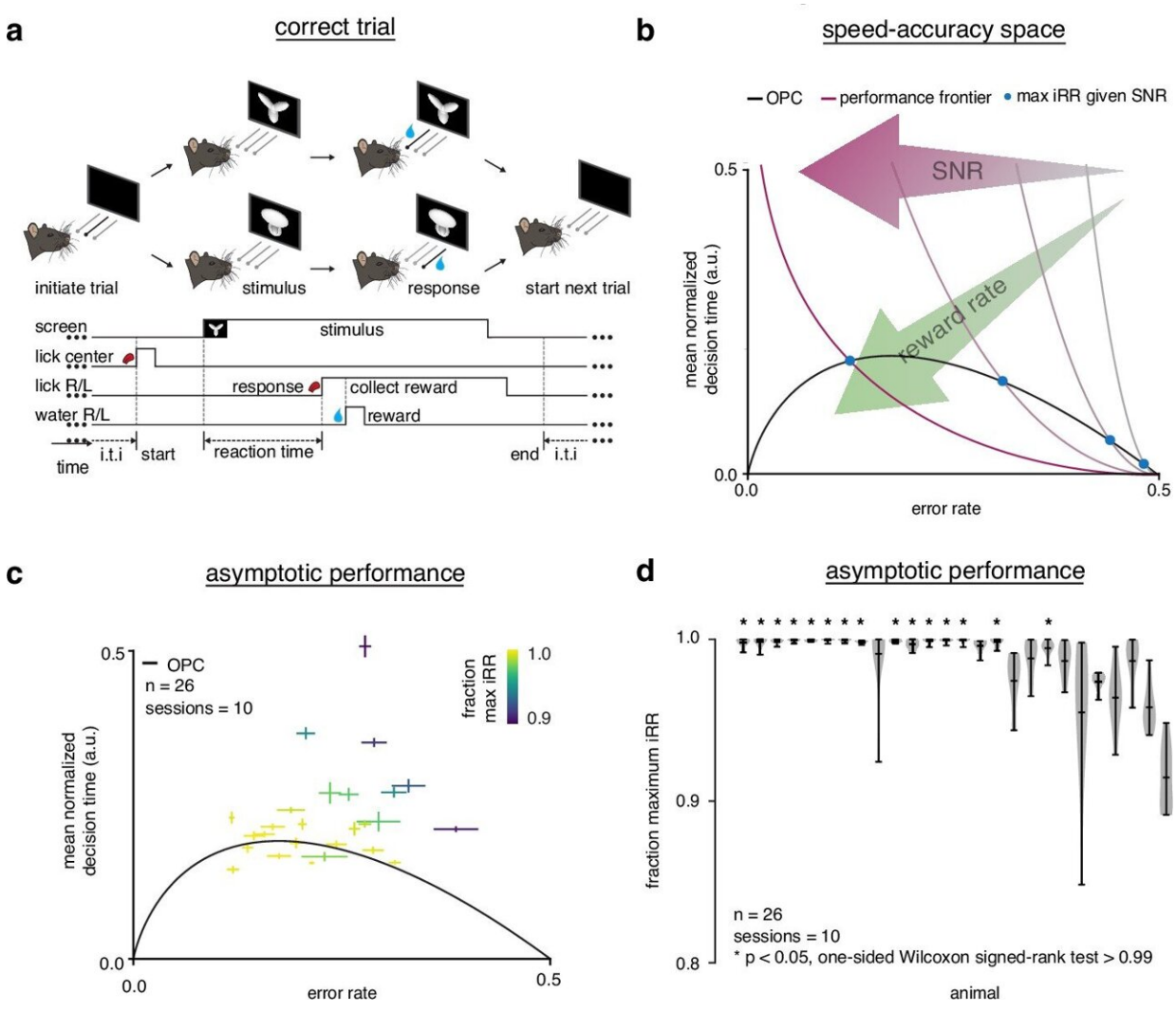


Trained rats solve the speed-accuracy trade-off. (a) Rat initiates trial by licking center port, one of two visual stimuli appears on the screen, rat chooses correct left/right response port for that stimulus and receives a water reward. (b) Speed-

accuracy space: a decision making agent's ER and mean normalized DT (a normalization of DT based on the average timing between one trial and the next, see Methods). Assuming a simple drift-diffusion process, agents that maximize iRR (see Methods) must lie on an optimal performance curve (OPC, black trace) (Bogacz et al., 2006). Points on the OPC relate error rate to mean normalized decision time, where the normalization takes account of task timing parameters (e.g. average response-to-stimulus interval). For a given SNR, an agent's performance must lie on a performance frontier swept out by the set of possible threshold-to-drift ratios and their corresponding error rates and mean normalized decision times. The intersection point between the performance frontier and the OPC is the error rate and mean normalized decision time combination that maximizes iRR for that SNR. Any other point along the performance frontier, whether above or below the OPC, will achieve a suboptimal. iRR Overall, iRR increases toward the bottom left with maximal instantaneous reward rate at error rate = 0.0 and mean normalized decision time = 0.0. (c) Mean performance across 10 sessions for trained rats (n=26) at asymptotic performance plotted in speed-accuracy space. Each cross is a different rat. Color indicates fraction of maximum instantaneous reward rate (iRR) as determined by each rat's performance frontier. Errors are bootstrapped SEMs. (d) Violin plots depicting fraction of maximum, iRR a quantification of distance to the OPC, for same rats and same sessions as c. Fraction of maximum iRR is a comparison of an agent's current iRR with its optimal iRR given its inferred SNR. Approximately 15 of 26 (~60%) of rats attain greater than 99% fraction maximum iRRs for their individual inferred SNRs. * denotes p 0.99. Credit: *eLife* (2023). DOI: 10.7554/eLife.64978

Scientists have provided evidence for the cognitive control of learning in rats, showing they can estimate the long-term value of learning and adapt their decision-making strategy to take advantage of learning opportunities.

The findings suggest that by taking longer over a decision, rats may sacrifice immediate rewards to increase their learning outcomes and

achieve greater rewards over the entire course of a task. The results are published today in *eLife*.

An established principle of behavioral neuroscience is the speed-accuracy trade-off, which is seen across many species, from rodents to primates. The principle describes the relationship between an individual's willingness to respond slowly and make fewer errors compared to their willingness to respond quickly and risk making more errors.

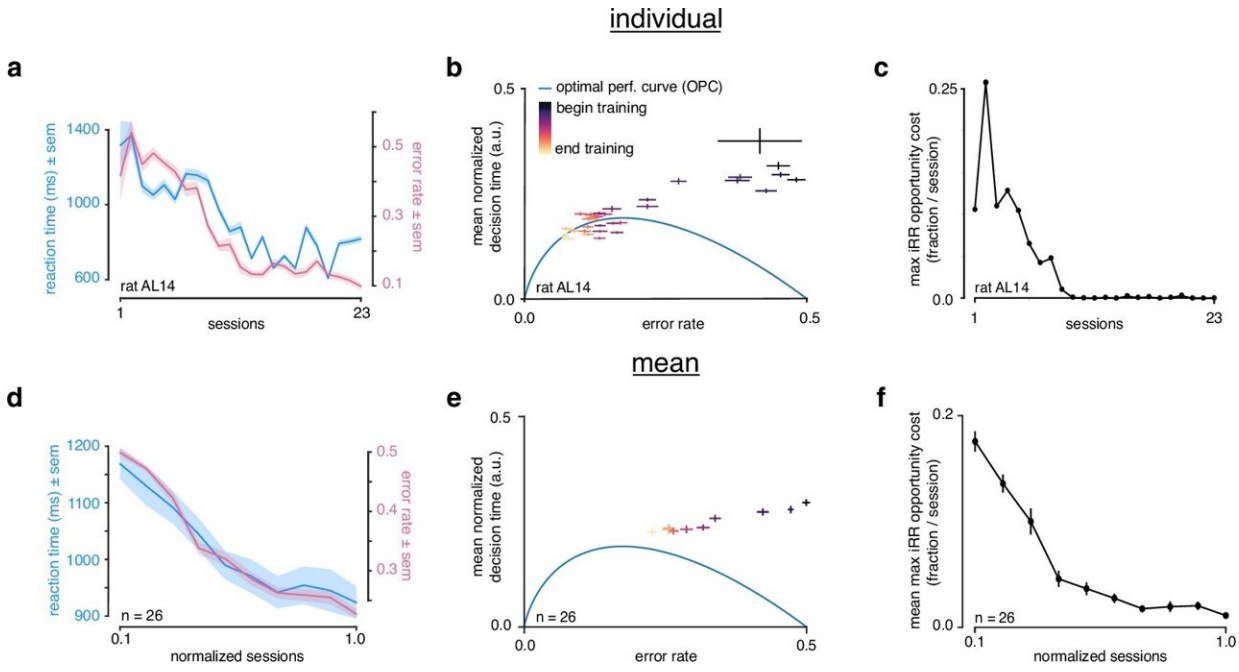
"Many studies in this area have focused on the speed-accuracy trade-off, without taking learning outcomes into account," says lead author Javier Masís, who at the time was a Ph.D. student at the Department of Molecular and Cellular Biology, and the Center for Brain Science, Harvard University, US, and is now a Presidential Postdoctoral Research Fellow at the Princeton Neuroscience Institute at Princeton University, U.S. "We aimed to investigate the difficult intertemporal choice problem that exists when you have the possibility to improve your behavior through learning."

For their study, Masís and colleagues sought to first establish whether rats were able to solve the speed-accuracy trade-off. The team set up an experiment where rats, upon seeing one of two visual objects that could vary in their size and rotation, decided whether the visual object was the one that corresponded to a left response, or a right response, and licked the corresponding touch-sensitive port once they had decided. If the rats licked the correct port, they were rewarded with water, and if they licked the wrong port, they were given a timeout.

The team investigated the relationship between error rate (ER) and reaction time (RT) during these trials, using the Drift-Diffusion Model (DDM)—a standard decision-making model in psychology and neuroscience in which the decision maker accumulates evidence through

time until the level of evidence for one alternative reaches a threshold.

The subject's threshold level controls the speed-accuracy trade-off. Using a low-threshold yields fast but error-prone responses, whereas a high-threshold yields slow, but accurate responses. For every difficulty level, however, there is a best threshold to set that optimally balances speed and accuracy, allowing the decision maker to maximize their instantaneous reward rate (iRR). Across difficulties, this behavior can be summarized through a relationship between ER and RT called the optimal performance curve (OPC). After learning the task fully, over half of the trained rats reached the OPC, demonstrating that well-trained rats solve the speed-accuracy trade-off.



Rats do not greedily maximize instantaneous reward rate during learning. (a) Reaction time (blue) and error rate (pink) for an example subject (rat AL14) across 23 sessions. (b) Learning trajectory of individual subject (rat AL14) in speed-accuracy space. Color map indicates training time. Optimal performance curve (OPC) in blue. (c) Maximum iRR opportunity cost (see Methods) for individual subject (rat AL14). (d) Mean reaction time (blue) and error rate

(pink) for n=26 rats during learning. Sessions across subjects were transformed into normalized sessions, averaged and binned to show learning across 10 bins. Normalized training time allows averaging across subjects with different learning rates (see Methods). (e) Learning trajectory of n=26 rats in speed-accuracy space. Color map and OPC as in a. (f) Maximum iRR opportunity cost of rats in b throughout learning. Errors reflect within-subject session SEMs for a and b and across-subject session SEMs for d, e, and f. Credit: *eLife* (2023). DOI: 10.7554/eLife.64978

At the start of training, though, all rats gave up over 20% of their iRR, whereas towards the end, most rats near optimally maximized iRR. This prompted the question: If rats maximize instantaneous rewards by the end of learning, what governs their strategy at the beginning of learning?

To answer this, the team adapted the DDM as a recurrent neural network (RNN) that could learn over time and developed the Learning Drift-Diffusion Model (LDDM), enabling them to investigate how long-term perceptual learning across many trials is influenced by the choice of decision time in individual trials.

The model was designed with simplicity in mind, to highlight key qualitative trade-offs between learning speed and decision strategy. The analyses from this model suggested that rats adopt a "non-greedy" strategy that trades initial rewards to prioritize learning and therefore maximize total reward over the course of the task. They also demonstrated that longer initial reaction times lead to faster learning and higher reward, both in an experimental and simulated environment.

The authors call for further studies to consolidate these findings. The current study is limited by the use of the DDM to estimate improved learning. The DDM, and therefore LDDM, is a simple model that is a powerful theoretical tool for understanding specific types of simple

choice behavior that can be studied in the lab, but it is not capable of quantitatively describing more naturalistic decision-making behavior. Furthermore, the study focuses on one visual perceptual task; the authors therefore encourage further work with other learnable tasks across difficulties, sensory modalities and organisms.

"Our results provide a new view of the speed-accuracy trade-off by showing that perceptual decision-making behavior is strongly shaped by the stringent requirement to learn quickly," claims senior author Andrew Saxe, previously a postdoctoral research associate at the Department of Experimental Psychology, University of Oxford, UK, and now Sir Henry Dale Fellow and Associate Professor at the Gatsby Computational Unit and Sainsbury Wellcome Center, University College London, UK.

"A key principle that our study propounds," explains Javier Masís, "is that natural agents take into account the fact that they can improve through learning, and that they can and do shape the rate of that improvement through their choices. Not only is the world we live in non-stationary; we are also non-stationary, and we take that into account as we move around the world making choices."

"You don't learn the piano by futzing around the keys occasionally," adds Saxe. "You decide to practice, and you practice at the expense of other more immediately rewarding activities because you know you'll improve and it'll probably be worth it in the end."

More information: Javier Masís et al, Strategically managing learning during perceptual decision making, *eLife* (2023). DOI: 10.7554/eLife.64978

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