Papers review: Kepecs' framework for decision confidence

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Papers

Adam Kepecs et al., “Neural Correlates, Computation and Behavioural Impact of Decision Confidence,” Nature 455, no. 7210 (September 2008): 227–31, https://doi.org/10.1038/nature07200.

Adam Kepecs and Zachary F. Mainen, “A Computational Framework for the Study of Confidence in Humans and Animals,” Philosophical Transactions of the Royal Society B: Biological Sciences 367, no. 1594 (May 19, 2012): 1322–37, https://doi.org/10.1098/rstb.2012.0037.

Scope

- Humans and other animals must often make decisions on the basis of imperfect evidence.
- Little is/was known about how the brain computes confidence estimates about decisions.
- Issue is explored combining behavioral analysis, computational modeling and neural recordings.

Behavioral study of confidence

Behavioral reports of confidence

- Explicit reports (via textual or numerical ratings) are only accessible to humans.
- Only implicit reports are possible for non-humans.

Confidence report protocols

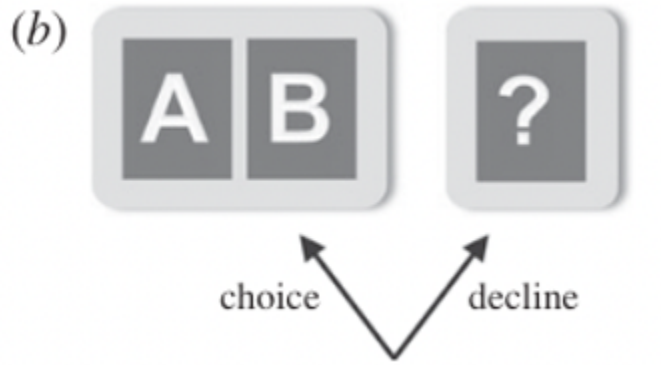
Uncertain option

- Add a third choice, the "uncertain option", to the available responses.
- Pioneered in experimental psychology nearly a century ago.
- Has been applied to monkeys, dolphins, rats and pigeons.
- Can be interpreted as a three-choice task solved by learning stimulus-response categories, without necessitating confidence estimations.



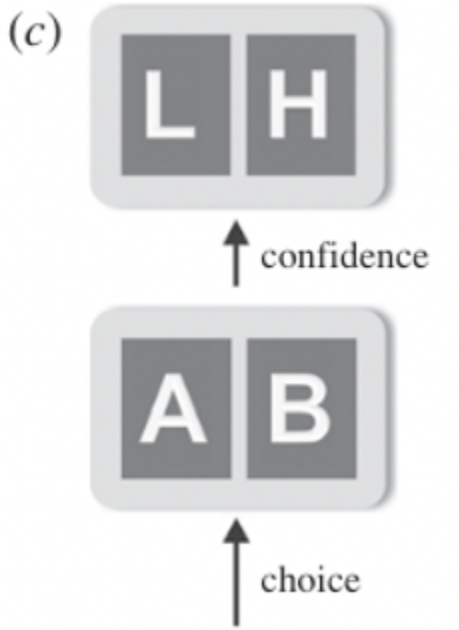
Decline (opt-out) option

- Add option of accepting or declining the test.
- Has been applied to monkeys, pigeons and rats.
- Rather than confidence, attention or motivation could explain the choice to answer or not.



Post-decision wagering

- The binary choice is followed by a bet on the reward. If the decision is correct, the wager amount is kept.
- Contrary to previous protocols, both choice and confidence are obtained on each trial.

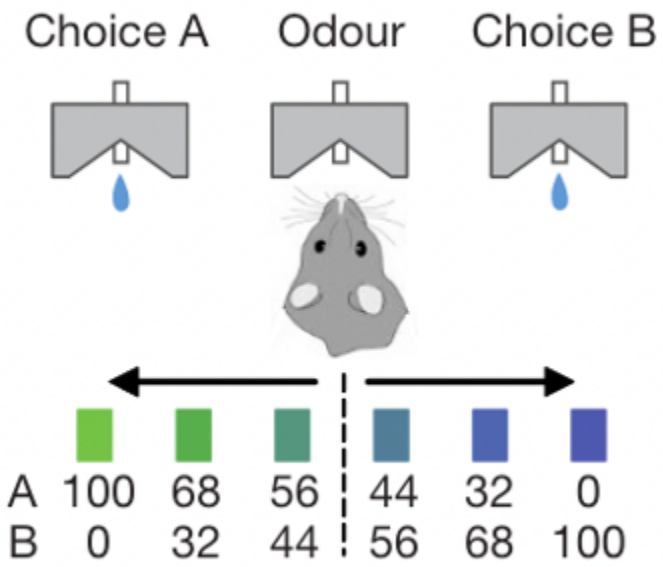


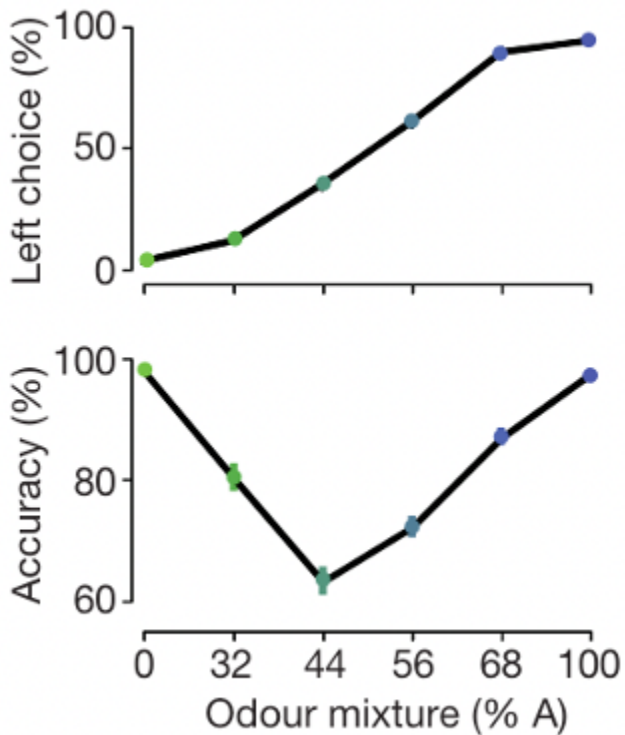
Decision restart

- After choice, subjects are given the option to either wait for their (potential) reward or abort the trial and start again.
- Form of post-decision wagering suitable to animals.

Experimental task

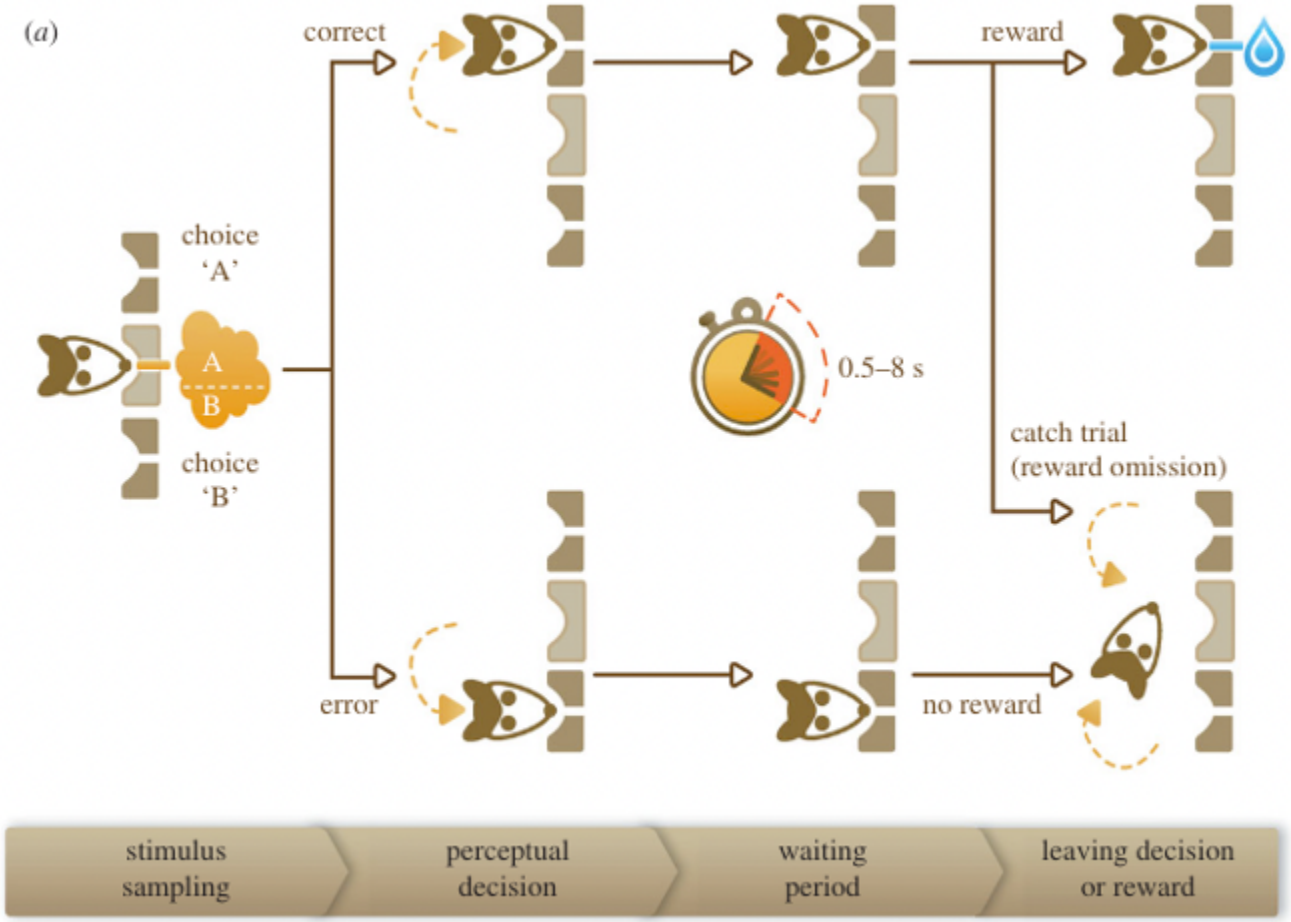
- Rats were trained to perform an odour categorization task, with water as a reward.
- On each trial, a binary mixture of two pure odorants was delivered.
- The decision difficulty was defined by the mixture ratio (50/50 = hardest).
- A variable reward delay was introduced.

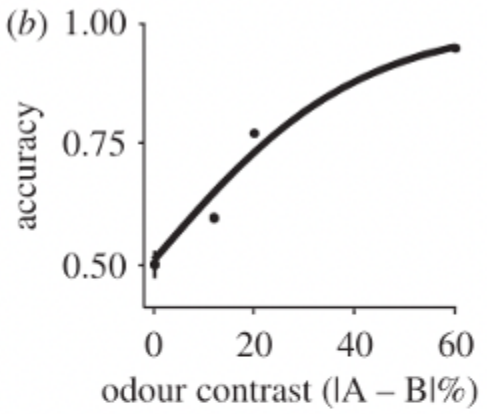


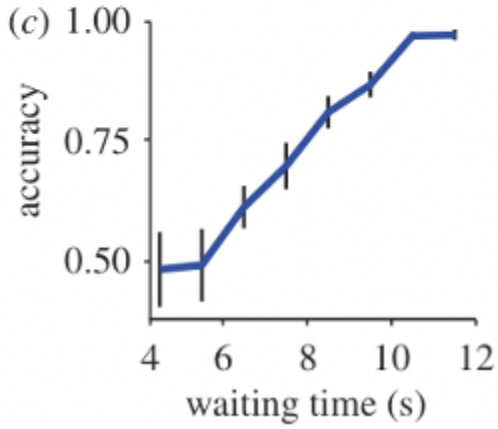


Task variation

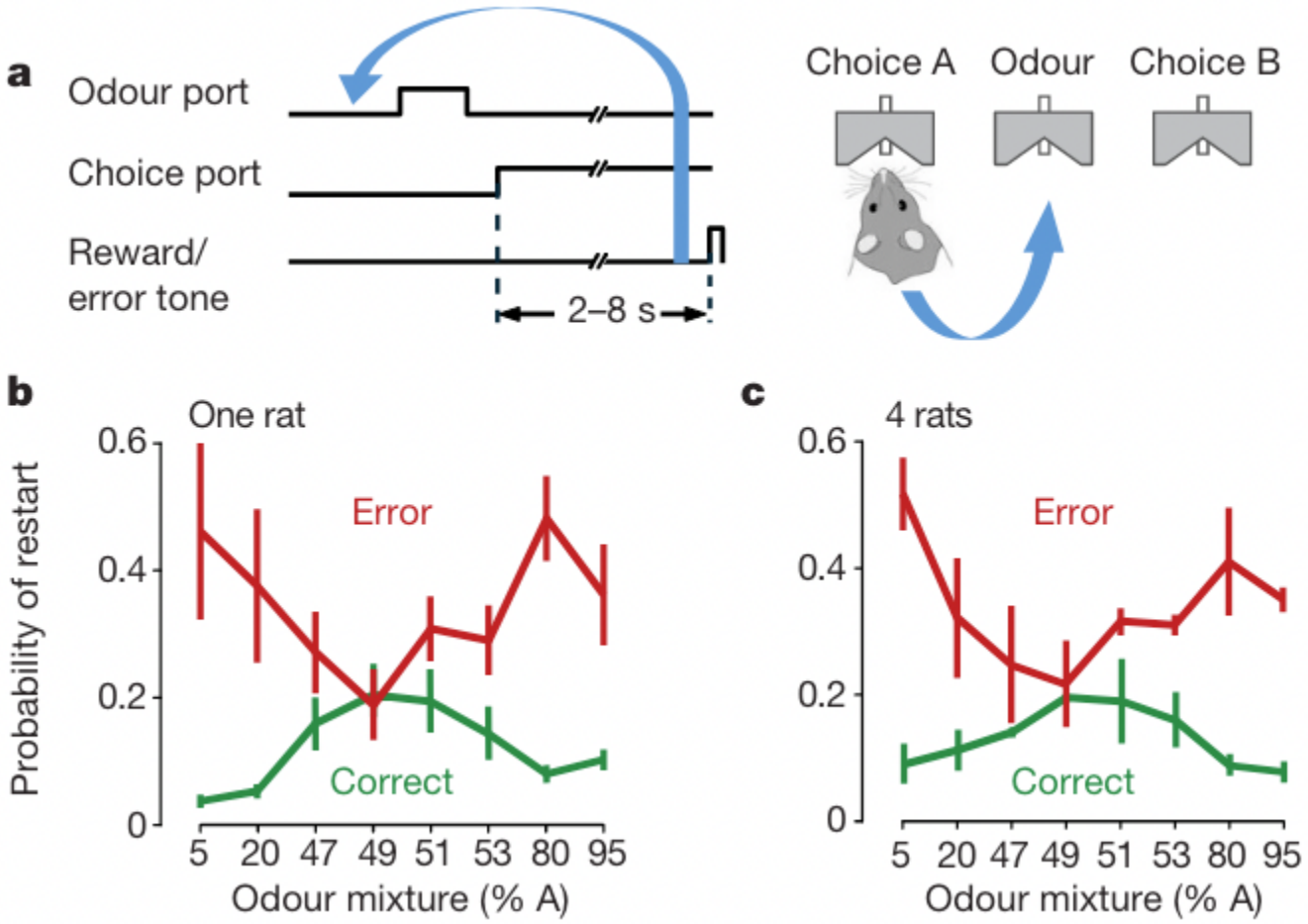
To assess confidence, reward delay was increased and decision restart was added.







Results


a
Odour port
Choice port
Reward/
error tone
2–8 s
Choice A
Odour
Choice B
b
One rat
Probability of restart
0.6
0.4
0.2
0
Error
Correct
5 20 47 49 51 53 80 95
Odour mixture (% A)
c
4 rats
0.6
0.4
0.2
0
Error
Correct
5 20 47 49 51 53 80 95
Odour mixture (% A)

Computational modeling of confidence

Defining confidence

- Confidence = estimate by the decision-maker of the probability that the decision is correct.
- Confidence is a form of uncertainty.

Simple confidence model

Formulation

- Stimulus s_i for the ith trial is defined as the log ratio of the odour mixture with Gaussian additive noise $\eta_{stim} \sim \mathcal{N}(0, \sigma_{stim})$.
- Choice boundary b_i is fixed at 0 with additive noise $\eta_{bound} \sim \mathcal{N}(0, \sigma_{bound})$.
- Choice is computed by comparing stimulus and boundary.
- Distance between them provides an estimate of decision confidence.

$$s_i = log\frac{[A]}{[B]} + \eta_{stim}$$

$$b_i = \eta_{bound}$$

$$c_i = \{\text{left}|s_i < b_i; \text{right}|s_i \geq b_i\}$$

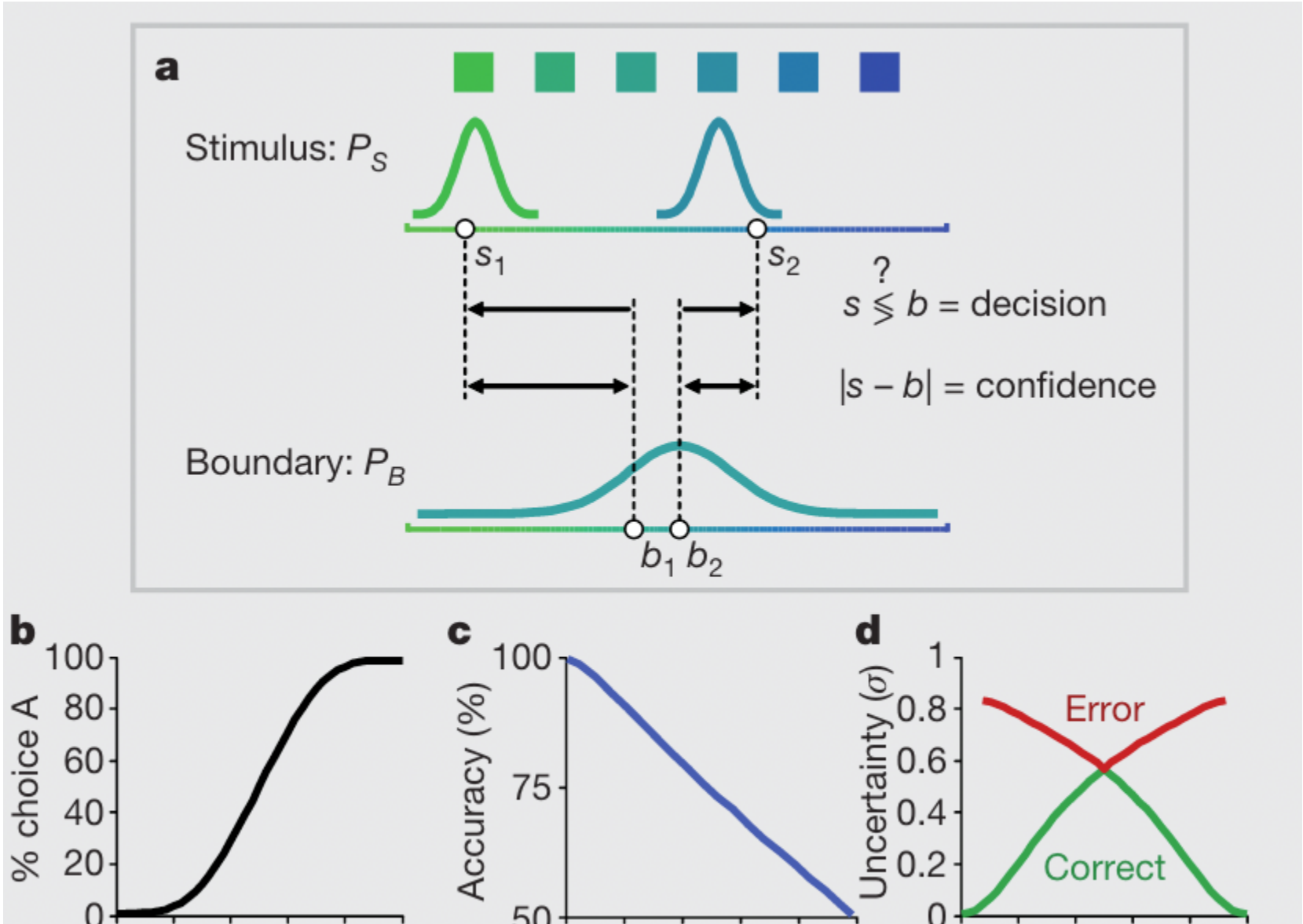
$$d_i = |s_i - b_i|$$

Confidence calibration

- The distance d_i must be calibrated and normalized to become a veridical estimator of decision outcome (linear relationship with accuracy).
- Sigmoid-like functions provide a good solution to this problem.
- Decision confidence δ_i is defined as the result of the calibration process.
- Decision uncertainty σ_i is defined as its contrary.

$$\delta_i = f(d_i) = \tan(|s_i - b_i|)$$
$$\sigma_i = 1 - \delta_i$$

Results


a
Stimulus: P_S
s_1
s_2
?
$s \lessgtr b$ = decision
$|s - b|$ = confidence
Boundary: P_B
b_1 b_2
b
% choice A
100
80
60
40
20
0
c
Accuracy (%)
100
75
50
d
Uncertainty (σ)
1
0.8
0.6
0.4
0.2
0
Error
Correct

Evidence accumulation model

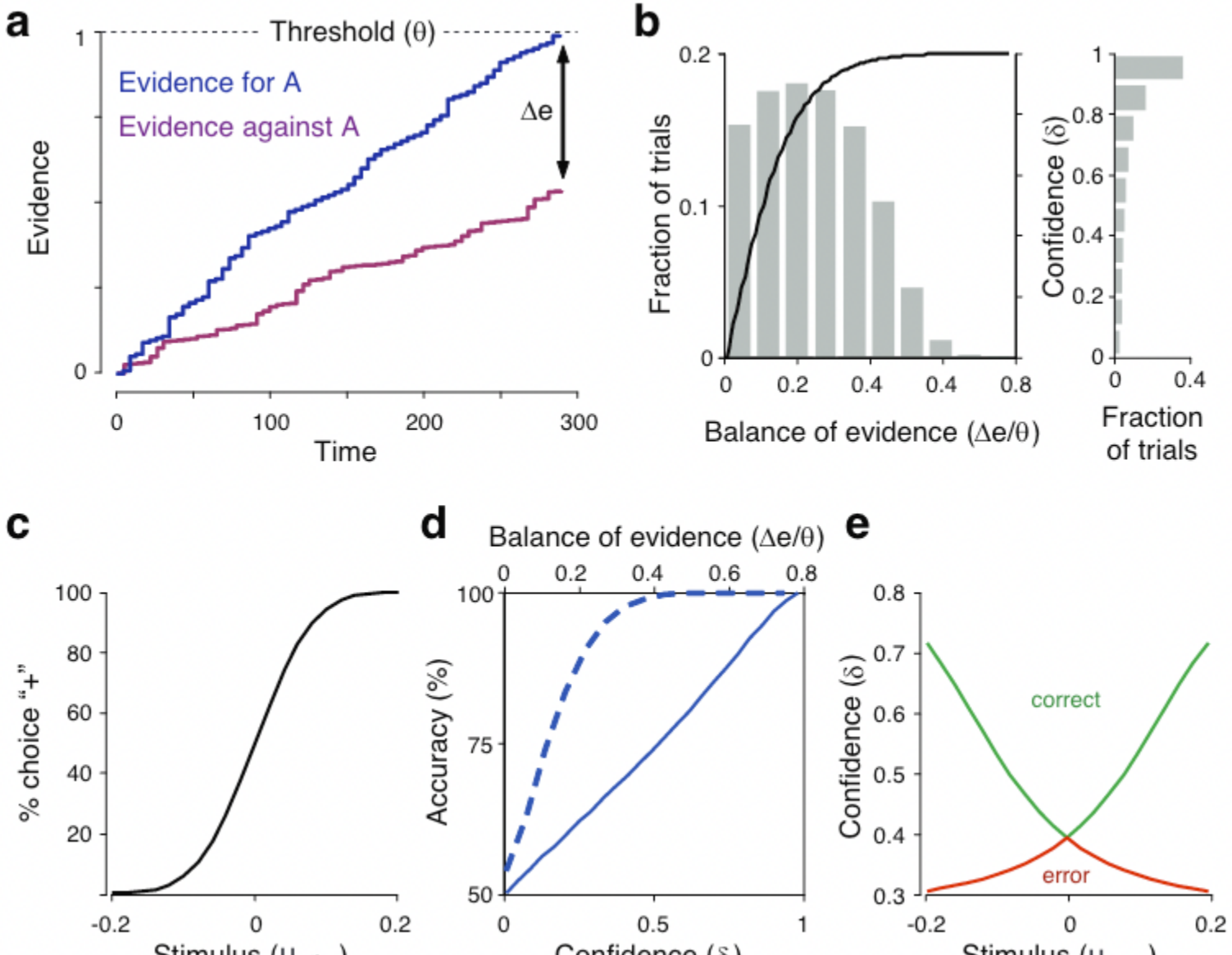
Formulation

- This class of models is able to account for other features of behavior, such as decision time (more details).
- In a race model, decision confidence can be estimated as the distance Δe_i between the accumulators once an accumulator reaches the threshold θ_i.
- The balance of evidence BoE results from the normalization of this distance.
- Calibration is necessary to turn confidence into a veridical estimator of decision outcome.

$$BoE_i = \Delta e_i / \theta_i$$

$$\delta_i = f(BoE_i) = \frac{2}{1 + e^{\frac{1}{3}\Delta e_i / \theta_i}}$$

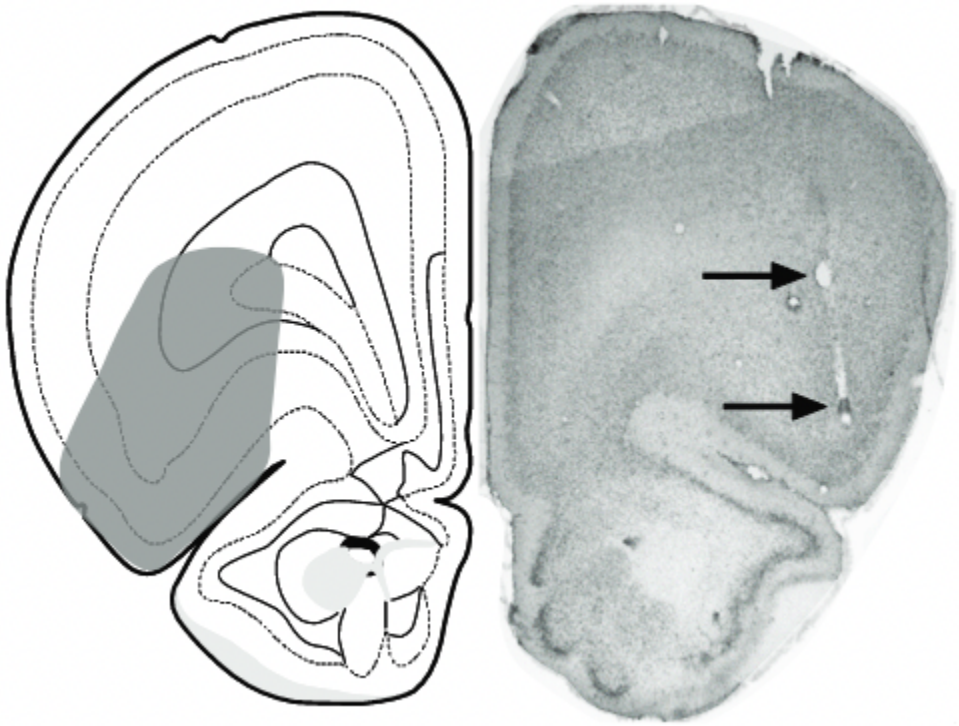
Results


a
Threshold (θ)
Evidence for A
Evidence against A
Δe
Evidence
Time
b
Fraction of trials
Balance of evidence (Δe/θ)
Confidence (δ)
Fraction of trials
c
% choice "+"
d
Balance of evidence (Δe/θ)
Accuracy (%)
e
Confidence (δ)
correct
error

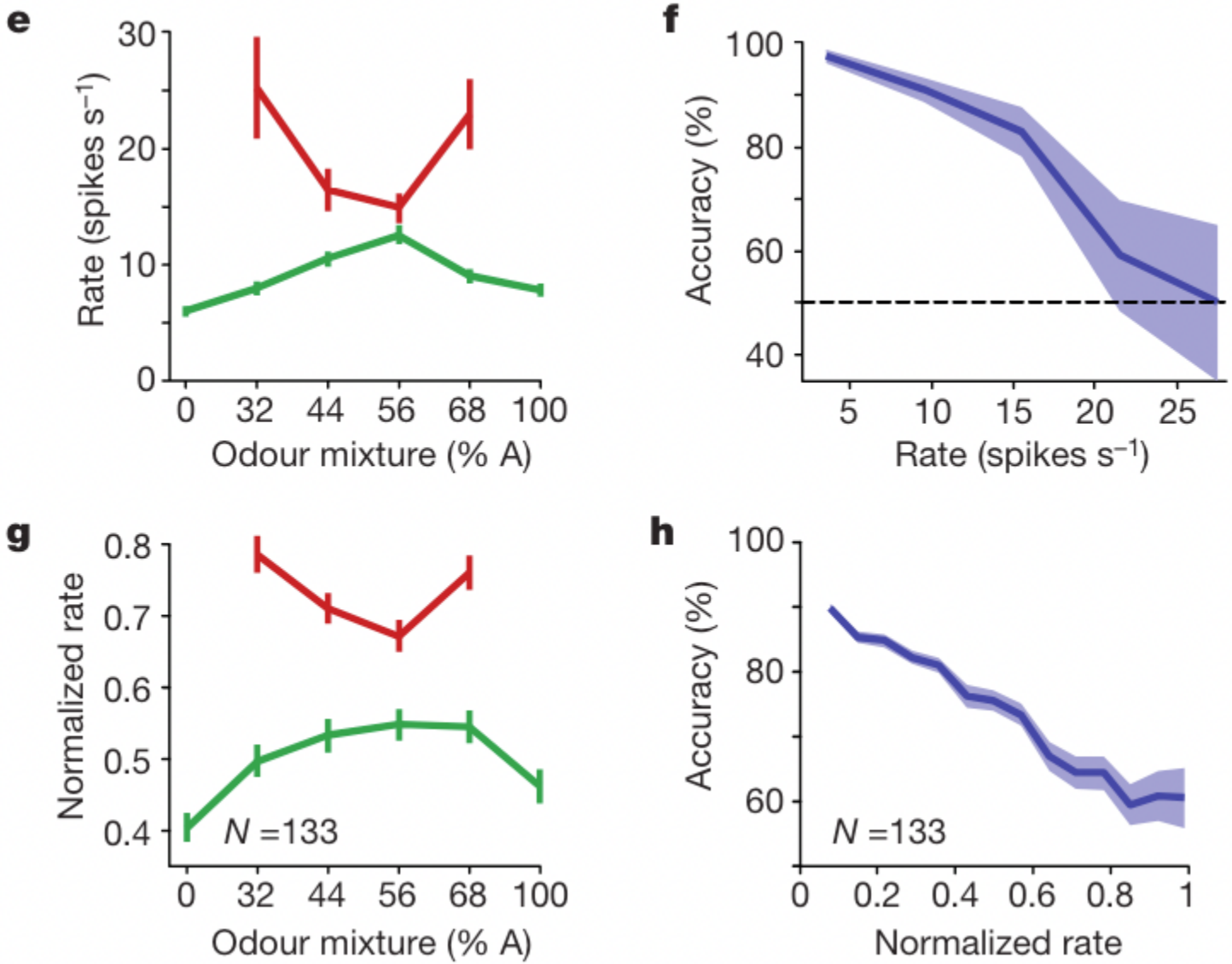
Neural correlates of confidence

Experimental setup

- Single neuron activity was recorded in rats' OFC during the olfactory mixture categorization task.
- The analysis was focused on the reward-anticipation period, assumed to be associated with confidence estimations.



Results


e
Rate (spikes s^{-1})
30
20
10
0
0 32 44 56 68 100
Odour mixture (% A)
f
Accuracy (%)
100
80
60
40
5 10 15 20 25
Rate (spikes s^{-1})
g
Normalized rate
0.8
0.7
0.6
0.5
0.4
N =133
0 32 44 56 68 100
Odour mixture (% A)
h
Accuracy (%)
100
80
60
N =133
0 0.2 0.4 0.6 0.8 1
Normalized rate

Interpretation

- The firing rates of many single neurons in the OFC of rats match closely to the predictions of confidence models.
- These cannot be readily explained by alternative mechanisms, such as learning stimulus–outcome associations.
- Rats not only show a neural correlate of decision confidence, but they can use such information in subsequent decisions to guide adaptive behaviour.

Takeaways

- Behavioral findings, computational modeling and neural correlates were integrated into a coherent framework for decision confidence.
- Confidence estimations may be a fundamental and ubiquitous component of decision-making in the brain.
- Estimating the confidence in a choice is little more complex than calculating the choice itself, and within reach of non-humans.