



Trait Somatic Anxiety is Associated with Reduced Directed Exploration and Underestimation of Uncertainty

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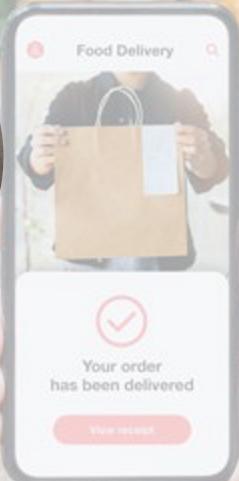
Explore/Exploit Dilemma (探索-利用困境)

Exploit 利用: Choose the current best option

Explore 探索: Forgo the current best option and choose something that could potentially be better

- Sacrificing immediate reward in exchange for information
- Crucial for maximizing long term reward in an uncertain environment.

Explore



Exploit



How does anxiety impact exploration?



- Avoidance behavior is closely related to insufficient exploration.
- Reduced spatial exploration is a behavioral signature of anxiety in rodent models¹.

But...

Mixed results:

- Anxious individuals show less exploration² and avoid uncertain options³.
- Anxious individuals show more exploration⁴ and seek information to reduce uncertainty⁵.
- Some studies did not find a relationship between anxiety and exploration⁶.

¹Bailey & Crawley, 2009; ²Smith et al., 2021; ³Charpentier et al., 2017; ⁴Aberg et al., 2021; ⁵Bennett et al., 2020; ⁶Zaller et al., 2021)

Multidimensionality of Anxiety and Exploration



Anxiety



Physical experience of anxiety (e.g., sweating, trembling)



Thought processes (e.g., rumination, worry)



- Considerable variation exists among individuals in the symptom profiles when experiencing anxiety.
- Somatic and cognitive dimensions are two major transdiagnostic factors that cut across DSM-defined anxiety disorders¹.
- Somatic and cognitive anxiety have distinct impacts on learning in an aversive environment².

*The current study focuses on trait anxiety.

(¹Sharp et al., 2015; ² Wise & Dolan, 2020)

Multidimensionality of Anxiety and Exploration



Uncertainty-driven

不确定性驱动探索

Directed

有向探索

Random

随机探索

Value-driven

价值驱动探索

Bias for information: Direct exploration towards the **Relatively Uncertain** option

Randomization of choice: Behave more randomly when **Total Uncertainty** is high

Choose option in proportion to their expected value

- People use a hybrid of uncertainty-driven and value-driven exploration strategies.¹

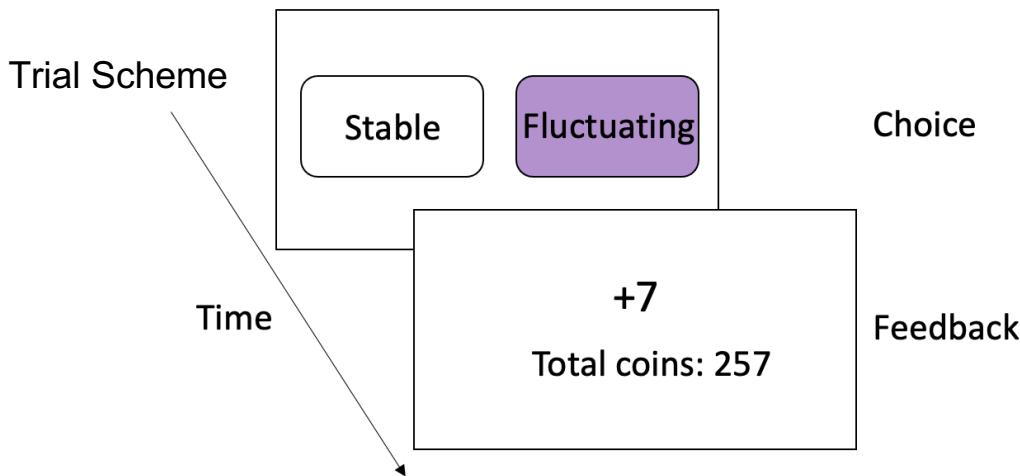
Somatic
Cognitive



Directed
Random
Value-driven

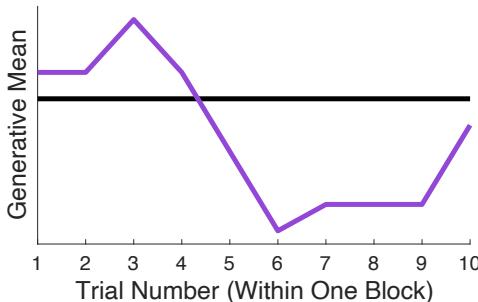
How do latent factors of trait anxiety impact different exploration strategies?

Two-armed Bandit Task (双臂老虎机)



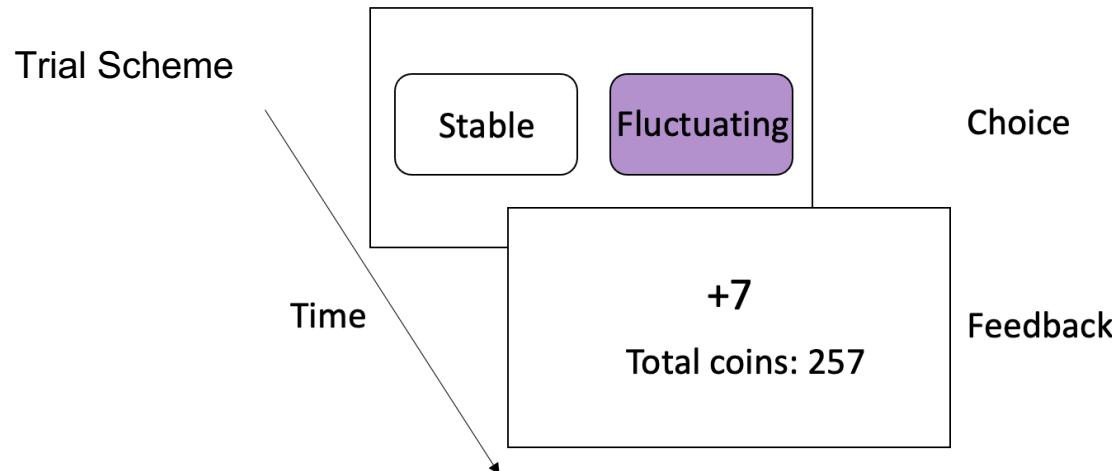
Slot machines deliver coins around their generative mean values. (Gaussian distribution)

- Stable (S): fixed mean value
- Fluctuating (F): drifting mean value



10	
12	
	6
10	
	14
8	
8	
9	
	7
	9

Two-armed Bandit Task



Four experiment conditions to manipulate Relative and Total Uncertainty:

- SF Stable Fluctuating
- SS Stable Stable
- FS Fluctuating Stable
- FF Fluctuating Fluctuating

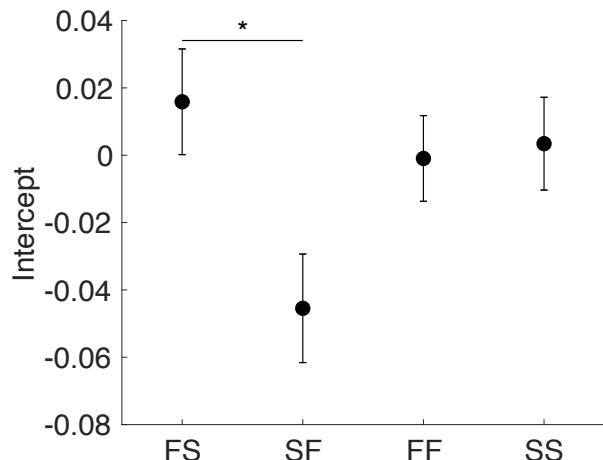
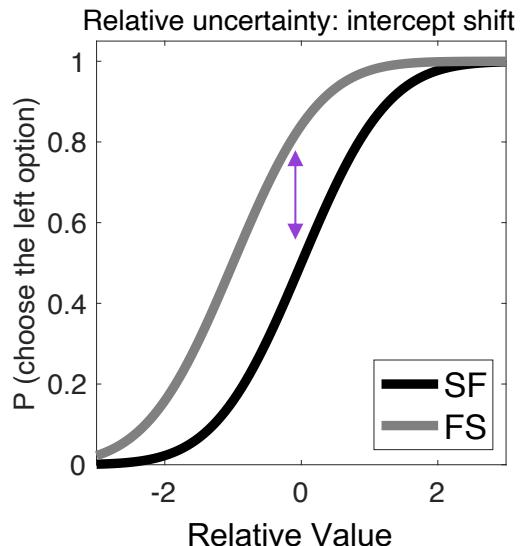
Experiment condition is reset at the beginning of each block.

Behavioral Signature of Different Exploration Strategies

Directed

Explore the option with higher **Relative Uncertainty** more frequently
- Prefer Fluctuating in Stable-Fluctuating and Fluctuating-Stable

Uncertainty-driven



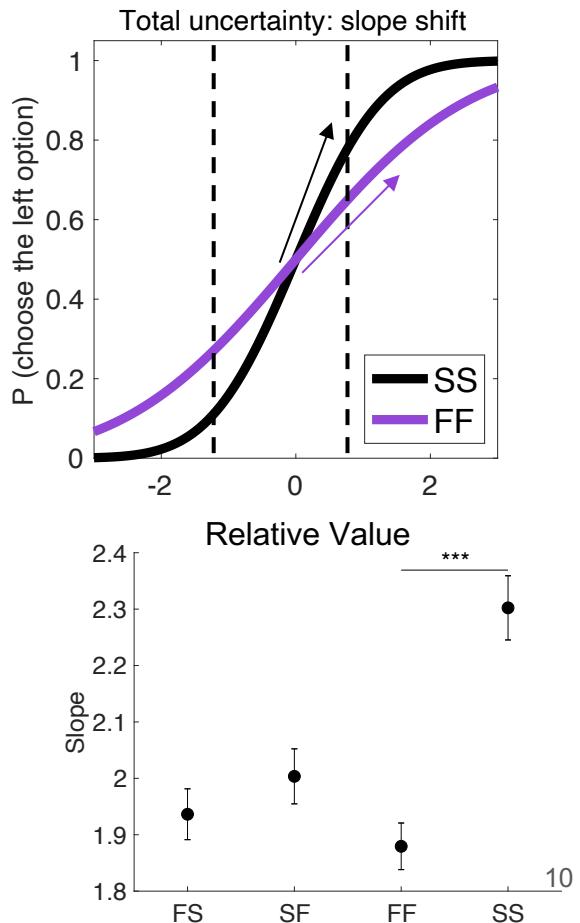
Behavioral Signature of Different Exploration Strategies

Uncertainty-driven

Random

Behave more randomly (i.e., explore more) when **Total Uncertainty** is high
- Behave more randomly in **Fluctuating-Fluctuating** vs. **Stable-Stable**

Independent manipulation of Relative and Total Uncertainty could causally impact directed and random exploration.



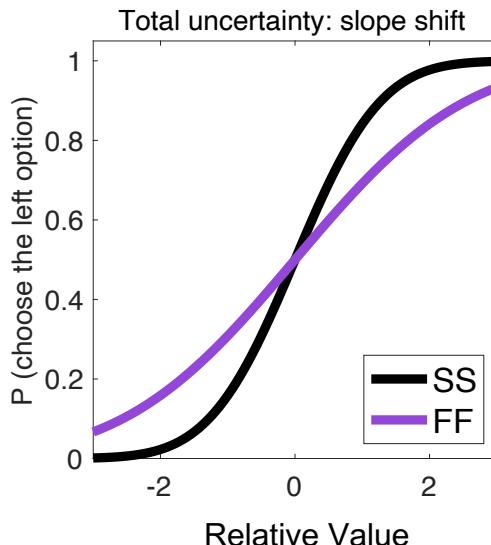
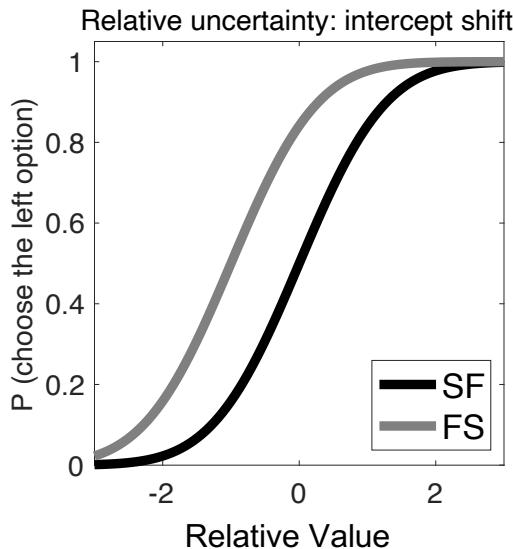
Behavioral Signature of Different Exploration Strategies

Uncertainty-driven

Directed

Random

Value-driven



Choose the option with higher **Relative Value** more frequently and explore the option with lower Relative Value from time to time

Behavioral Signature of Different Exploration Strategies

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Explore the option with higher **Relative Uncertainty** more frequently
- Prefer Fluctuating in Stable-Fluctuating and Fluctuating-Stable

Uncertainty-driven

Random

Behave more randomly (i.e., explore more) when **Total Uncertainty** is high
- Behave more randomly in Fluctuating-Fluctuating vs. Stable-Stable

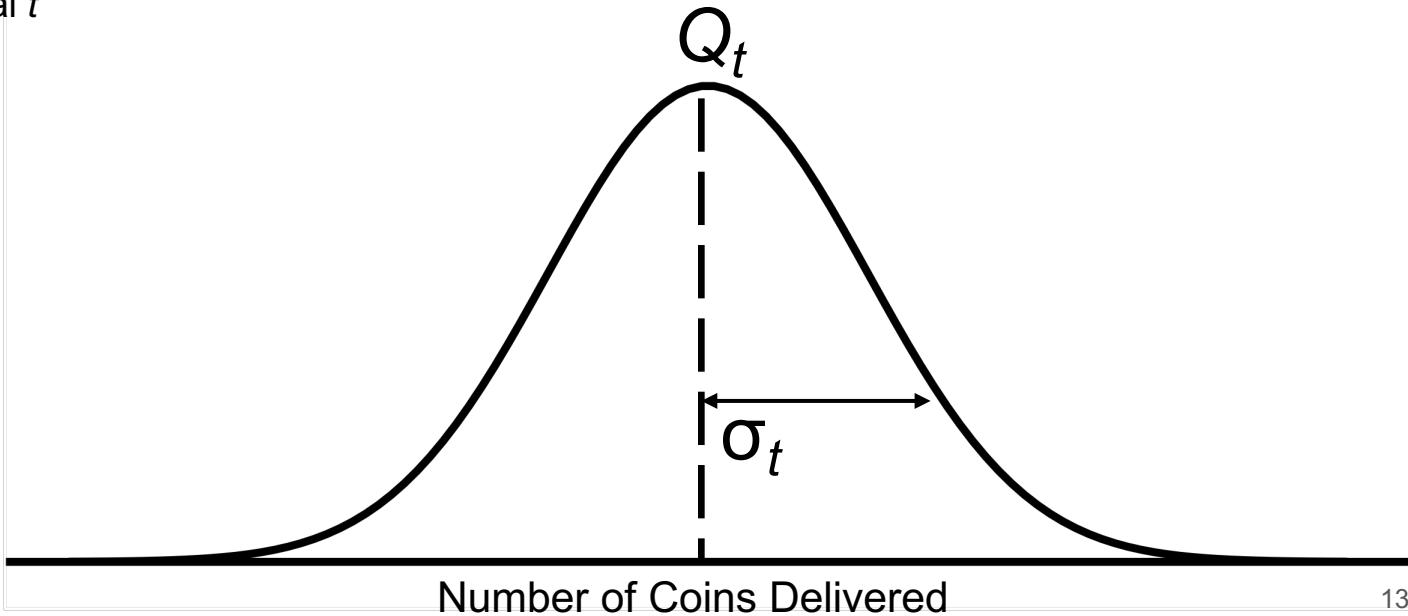
Value-driven

Choose the option with higher **Relative Value** more frequently and explore the option with lower Relative Value from time to time

Belief Update Process

Participants approximate an ideal Bayesian observer.

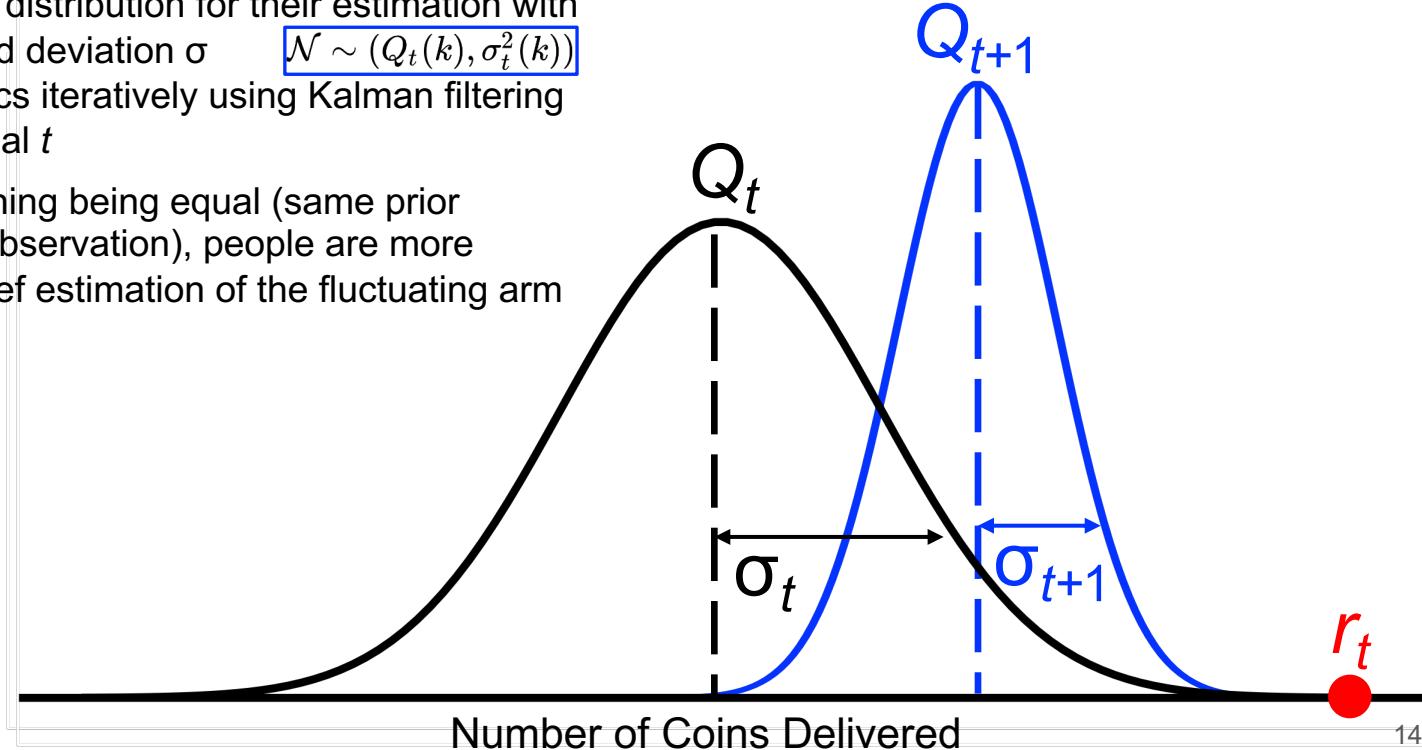
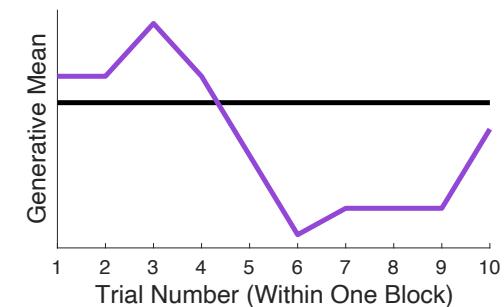
- Maintain a Gaussian distribution for their estimation with mean Q and standard deviation σ $\mathcal{N} \sim (Q_t(k), \sigma_t^2(k))$
- Update these statistics iteratively using Kalman filtering equations on each trial t



Belief Update Process

Participants approximate an ideal Bayesian observer.

- Maintain a Gaussian distribution for their estimation with mean Q and standard deviation σ $\mathcal{N} \sim (Q_t(k), \sigma_t^2(k))$
- Update these statistics iteratively using Kalman filtering equations on each trial t
- Intuition: With everything being equal (same prior distribution & same observation), people are more uncertain in their belief estimation of the fluctuating arm than the stable arm.

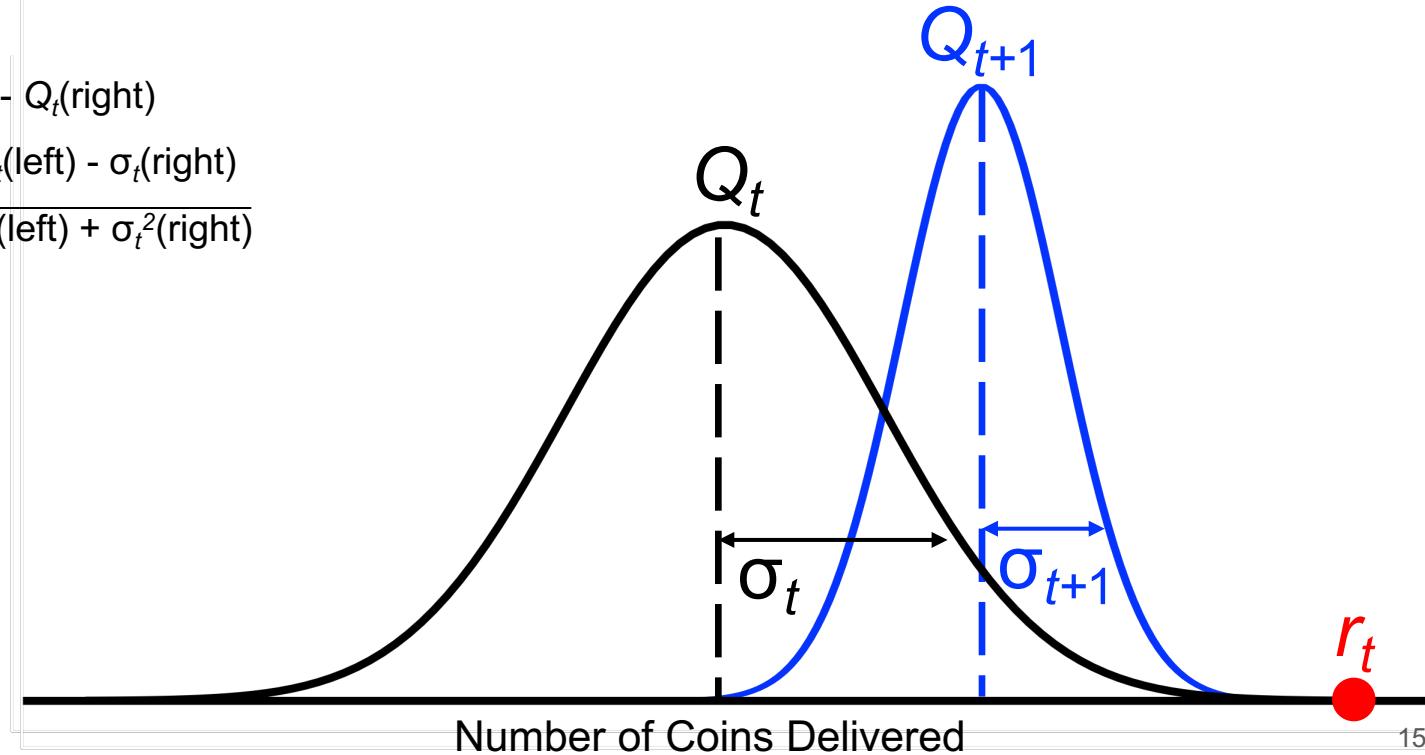


Choice Probability Analysis Across Conditions

Relative Value_t: $Q_t(\text{left}) - Q_t(\text{right})$

Relative Uncertainty_t: $\sigma_t(\text{left}) - \sigma_t(\text{right})$

Total Uncertainty_t: $\sqrt{\sigma_t^2(\text{left}) + \sigma_t^2(\text{right})}$



Choice Probability Analysis Across Conditions

Relative Value_t: $Q_t(\text{left}) - Q_t(\text{right})$

Relative Uncertainty_t: $\sigma_t(\text{left}) - \sigma_t(\text{right})$

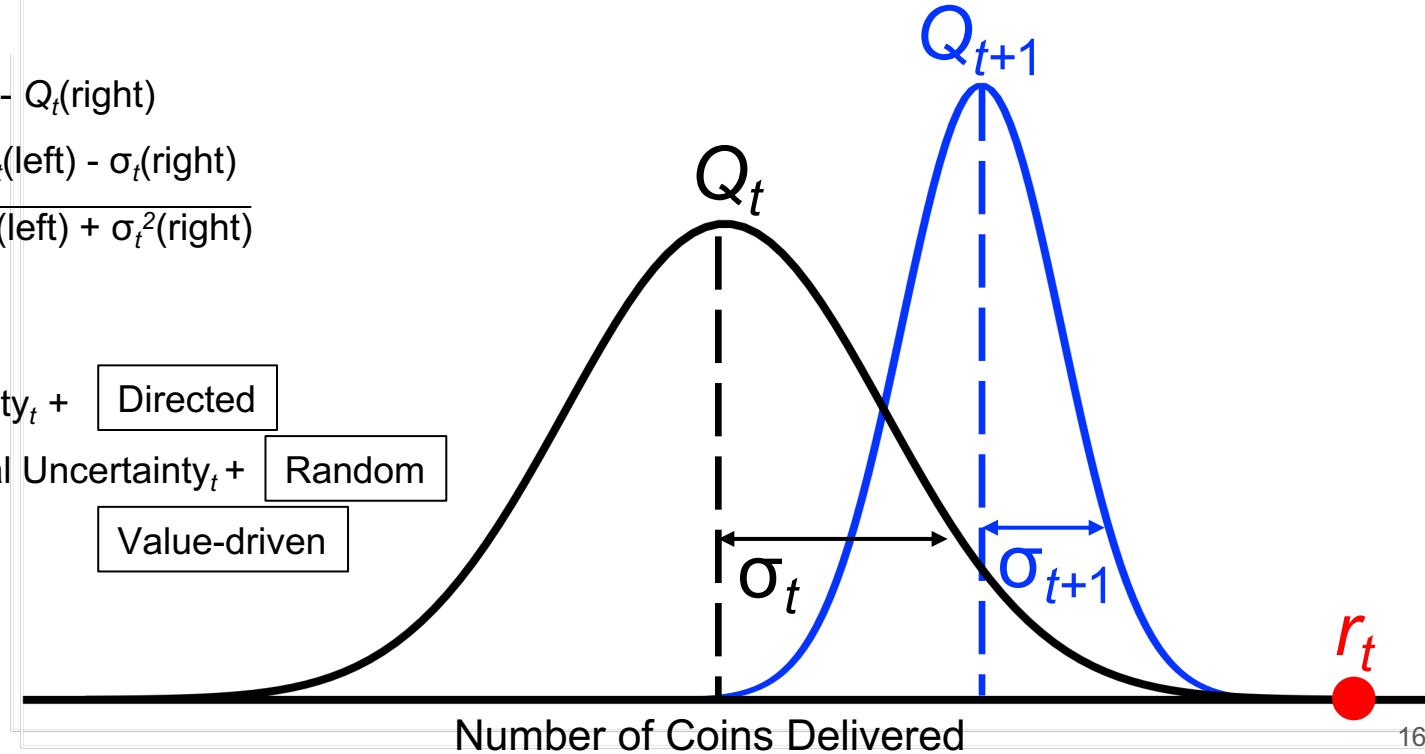
Total Uncertainty_t: $\sqrt{\sigma_t^2(\text{left}) + \sigma_t^2(\text{right})}$

$P(\text{choosing left}) =$

$\Phi(w_1 \text{Relative Uncertainty}_t +$ Directed)

$w_2 \text{Relative Value}_t / \text{Total Uncertainty}_t +$ Random

$w_3 \text{Relative Value}_t)$ Value-driven



A Hybrid of Exploration Strategies

$P(\text{choosing left}) =$

$\Phi(w_1 \text{Relative Uncertainty}_t +$

Directed

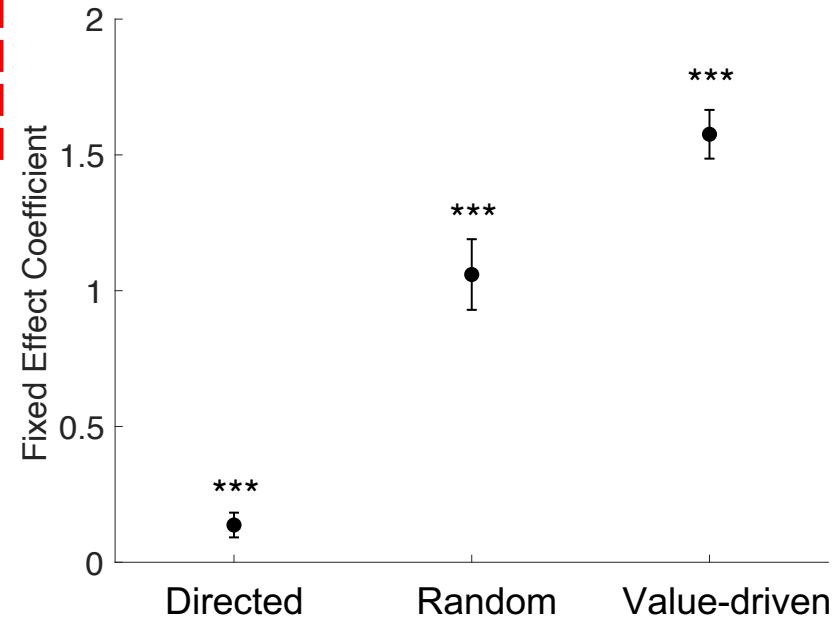
$w_2 \text{Relative Value}_t / \text{Total Uncertainty}_t +$

Random

$w_3 \text{Relative Value}_t)$

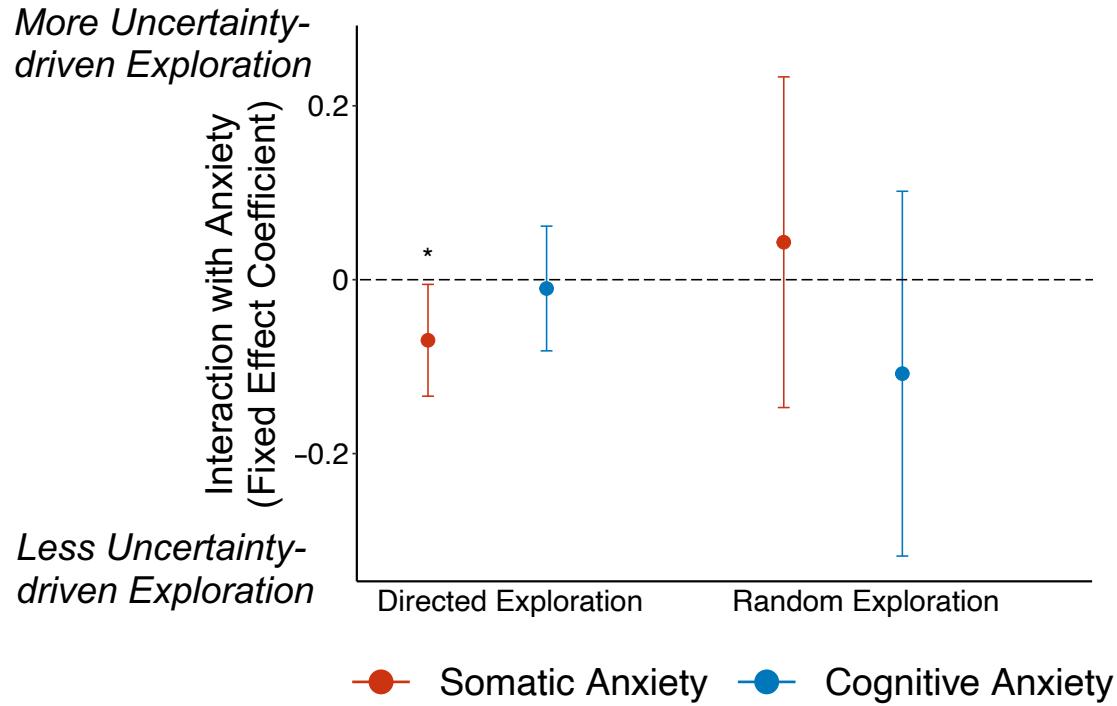
Value-driven

People use a hybrid of directed, random and value-driven exploration strategies.



Associations of Trait Anxiety with Uncertainty-driven Exploration

- People scoring high on somatic factor of anxiety showed reduced directed exploration, manifesting as avoiding the option with high Relative Uncertainty

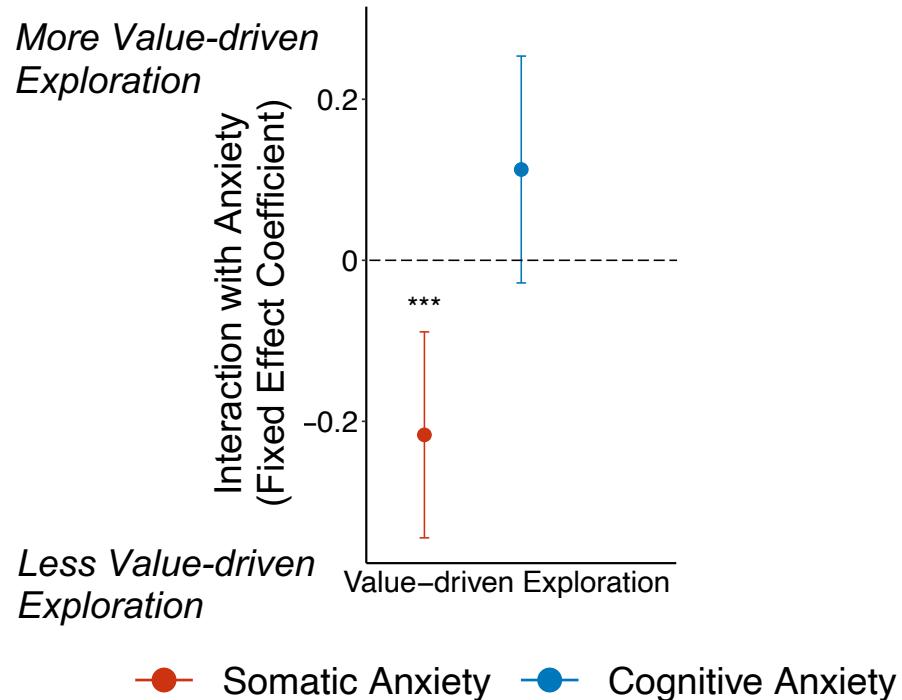


Somatic and cognitive anxiety scores were calculated based on exploratory factor analysis on STAI-T and STICSA-T

N = 501, 1 Error bar: 95% confidence interval; *: p < .05

Associations of Trait Anxiety with Value-driven Exploration

- People scoring high on somatic factor of anxiety demonstrated reduced value-driven exploration, being less likely to explore the option with low Relative Value.

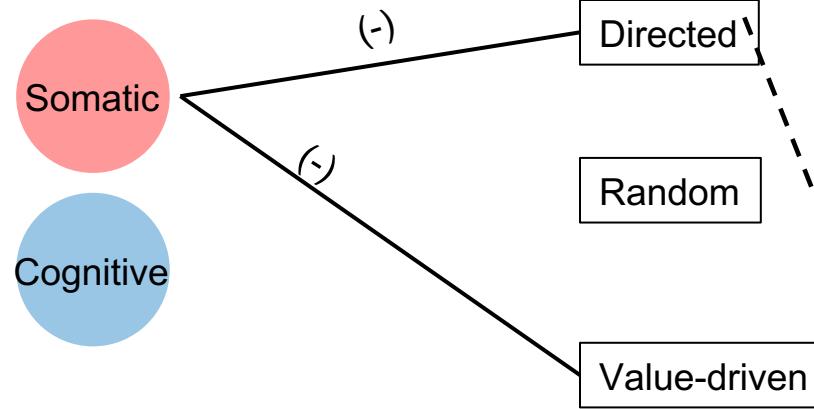


$N = 501$, 1 Error bar: 95% confidence interval; ***: $p < .001$

Trait Anxiety Factors



Exploration Strategies

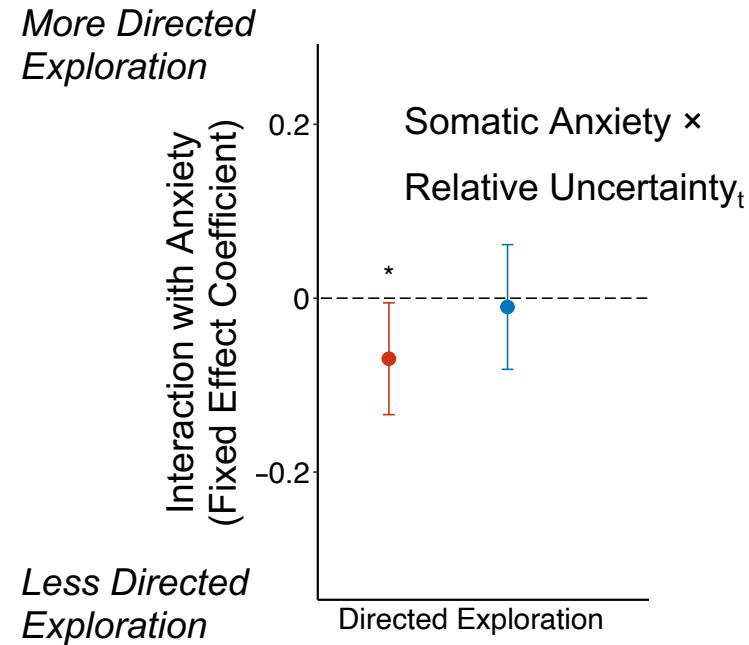


Potential mechanism
(Study 2)

- Trait somatic anxiety is associated with reduced directed exploration and reduced value-driven exploration (replicated in an independent sample, N=484).

Study 2: Subjective Estimate of Relative Uncertainty

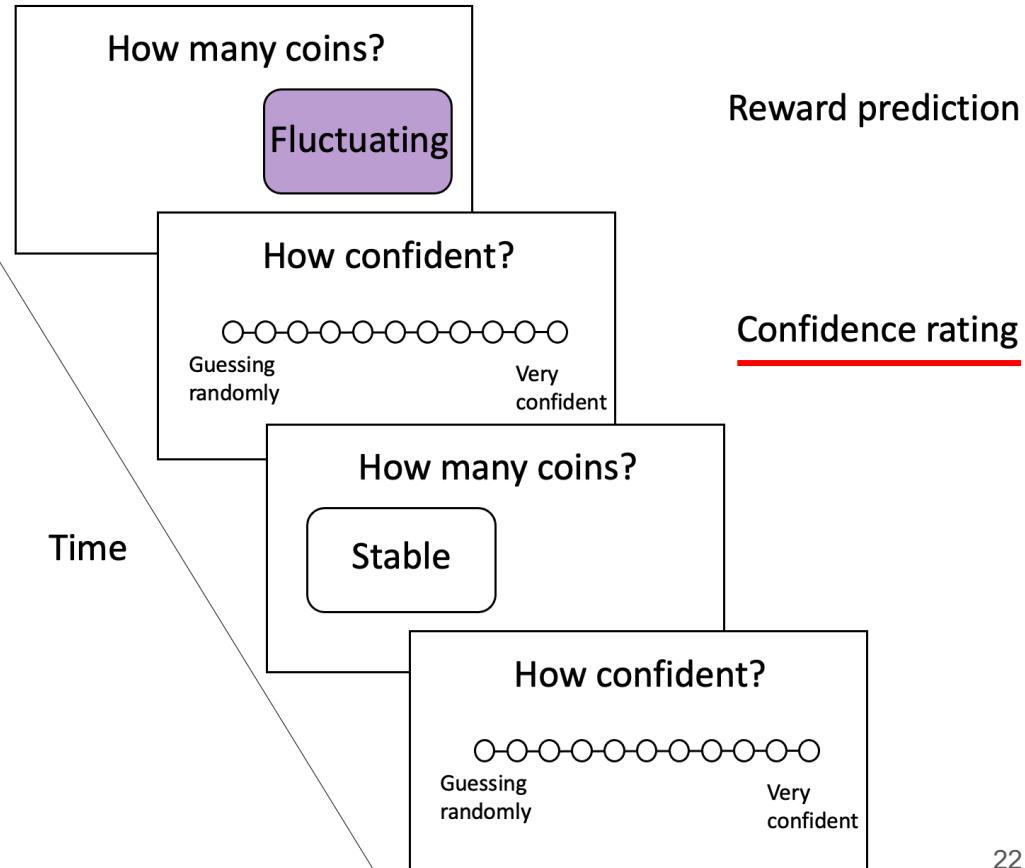
Does reduced directed exploration in somatic anxious individuals reflect an underestimation of Relative Uncertainty?



Prediction Task (Study 2)

- At the end of the block, participants were asked to predict how many coin each slot machine will generate and report their confidence. (no feedback)
- Subjective Relative Uncertainty** = Confidence(right) – Confidence(left)
- Objective Relative Uncertainty** = $\sigma_t(\text{left}) - \sigma_t(\text{right})$

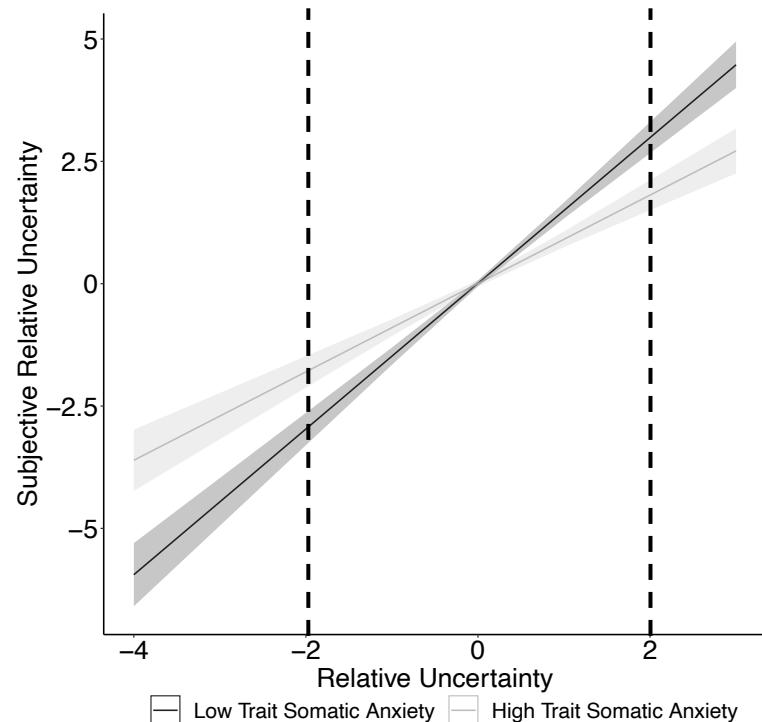
$$\text{Objective RU} = \text{Im}(\text{Subjective RU} \times \text{Anxiety})$$



Probe subjective estimates: Prediction Task

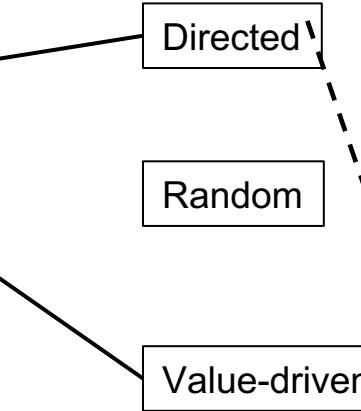
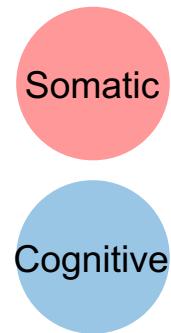
Objective RU ~ *Subjective RU* × Anxiety

Trait somatic anxiety is associated with underestimation of **Relative Uncertainty**. It is possible that somatic anxious individuals experience smaller information bonus when exploring the relatively uncertain option.



Trait Anxiety Factors

Exploration Strategies



Potential mechanism:
Underestimation of
Relative Uncertainty
(Study 2)

- Trait somatic anxiety is associated with reduced directed exploration and reduced value-driven exploration (replicated in an independent sample, N=484).
- We did not find evidence for the interactions between trait cognitive anxiety and exploration.
- Future studies should use a multidimensionality approach to understand the interaction between anxiety and the exploration process.

Pupil-linked arousal systems

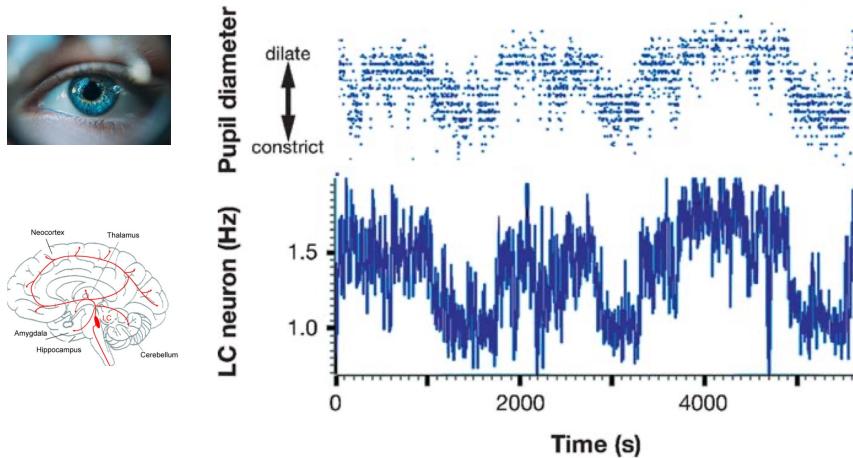


Pupil size (pupil dilation) is indicative of the arousal state, which is closely linked to learning under uncertainty¹.

Non-luminance-mediated pupil size change:

- covaries with uncertainty estimate in the environment².
- contains information about the upcoming decision³.

Pupil-linked LC-NE system



Locus coeruleus-norepinephrine (LC-NE) neuromodulatory system: one major source of pupil-linked arousal.

Tonic NE is associated with an increase in neuronal response to both task- and non-task related stimuli, promoting disengagement from the current task and *exploring* other options¹.

Pupil size is viewed as a real-time proxy of LC-NE activity².



Directed

Random

Value-driven

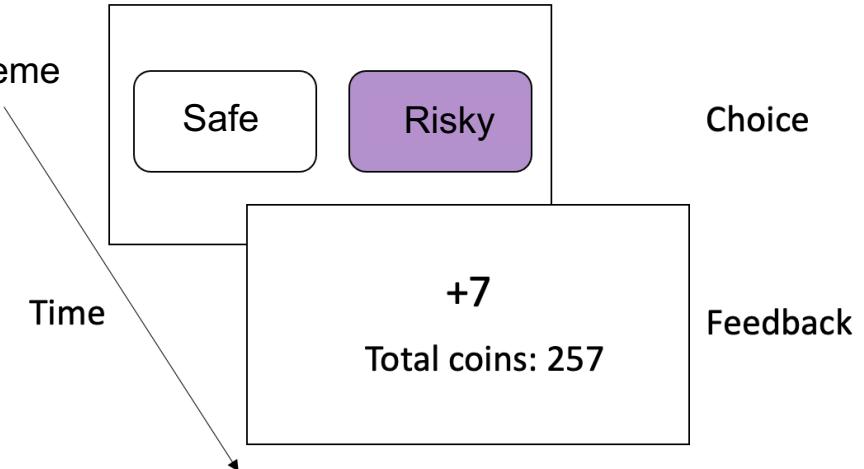
What is the role of pupil-linked arousal system in exploration?

Two-armed Bandit Task

Four experiment conditions to manipulate uncertainty:

- SR Safe Risky • RS Risky Safe
- SS Safe Safe • RR Risky Risky

Trial Scheme

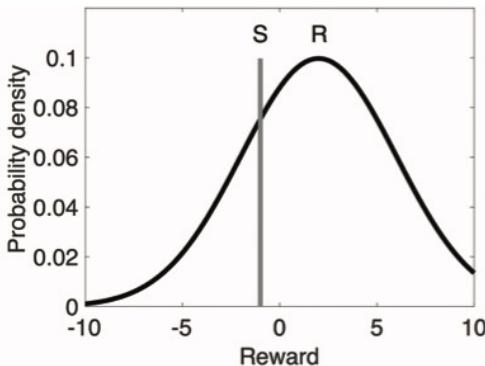


Choice

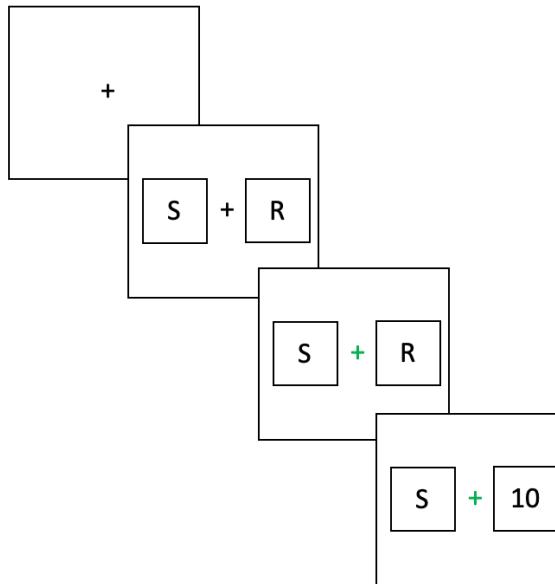
Feedback

Time

- Safe (S): deliver the same reward
- Risky (R): deliver coins around its generative mean value



Time window of interest: Trial Baseline (proxy of tonic NE)



Fixation (1s-2s)

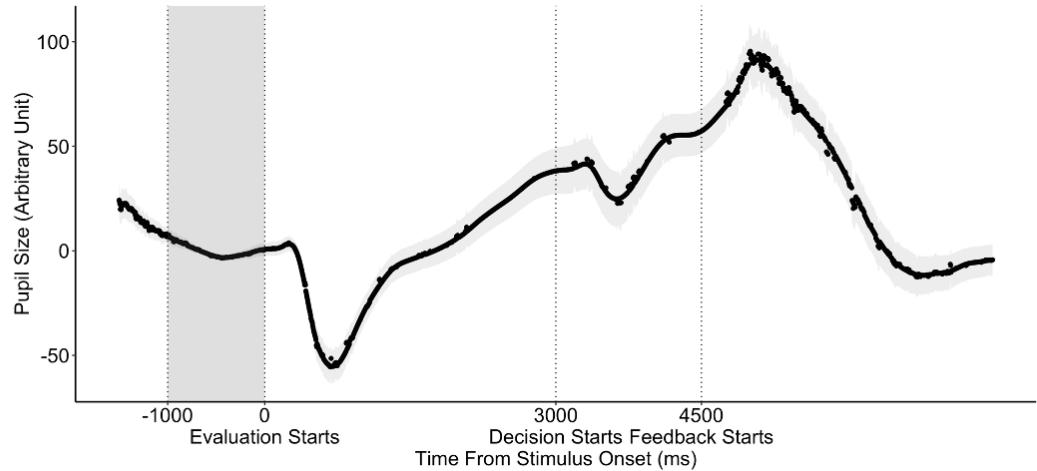
1000ms before stimulus onset

Evaluation (3s)

Decision (1.5s)

Feedback (3s)

Trial Baseline



Due to our block design, pupil size during the trial baseline contains task-related information rather than mere fluctuation.

Predicting pupil response using uncertainty and value estimates

Choice model

Relative Value_t: $Q_t(\text{left}) - Q_t(\text{right})$

Relative Uncertainty_t: $\sigma_t(\text{left}) - \sigma_t(\text{right})$

Total Uncertainty_t: $\sqrt{\sigma_t^2(\text{left}) + \sigma_t^2(\text{right})}$

P (choosing left) =

$\Phi(w_1 \text{Relative Uncertainty}_t +$

$w_2 \text{Relative Value}_t / \text{Total Uncertainty}_t +$

$w_3 \text{Relative Value}_t)$

Pupil model

Trial Baseline Pupil Size_t =

Relative Uncertainty_t +

Relative Value_t / Total Uncertainty_t +

Relative Value_t + **Total Uncertainty_t**

★ *Absolute Model*: $|\text{RU}| + |\text{V}/\text{TU}| + |\text{V}| + \text{TU}$

Directed Model: $|\text{RU}_{\text{directed}}| + |\text{V}_{\text{directed}}/\text{TU}| + |\text{V}_{\text{directed}}| + \text{TU}$

Pupil size encodes total uncertainty

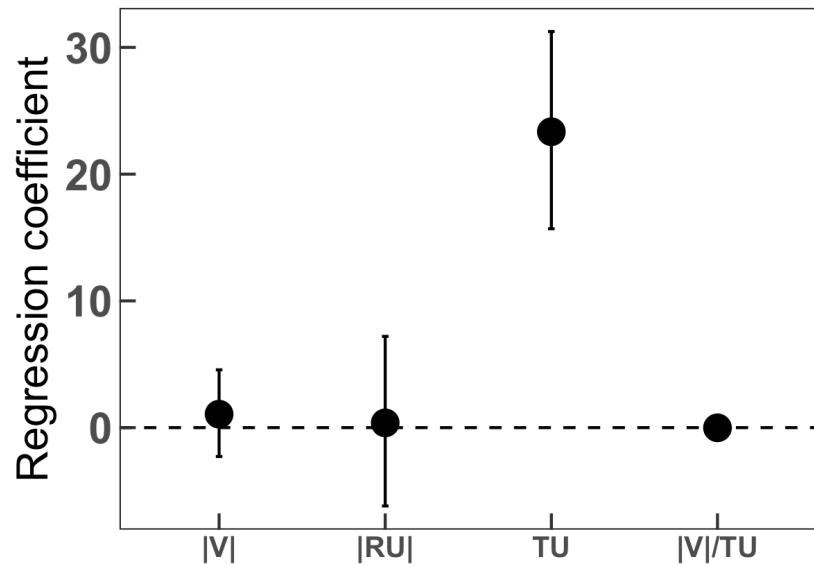
Trial Baseline Pupil Size_t =

$|Relative\ Uncertainty_t| +$

$|Relative\ Value_t| / Total\ Uncertainty_t +$

$|Relative\ Value_t| + \text{Total Uncertainty}_t$

Higher total uncertainty is associated with larger pupil size during the trial baseline.



$N = 48$, Error bar = 95% Credible Interval

RU: Relative Uncertainty; TU: Total Uncertainty; V: Relative Value

Pupil size encodes total uncertainty

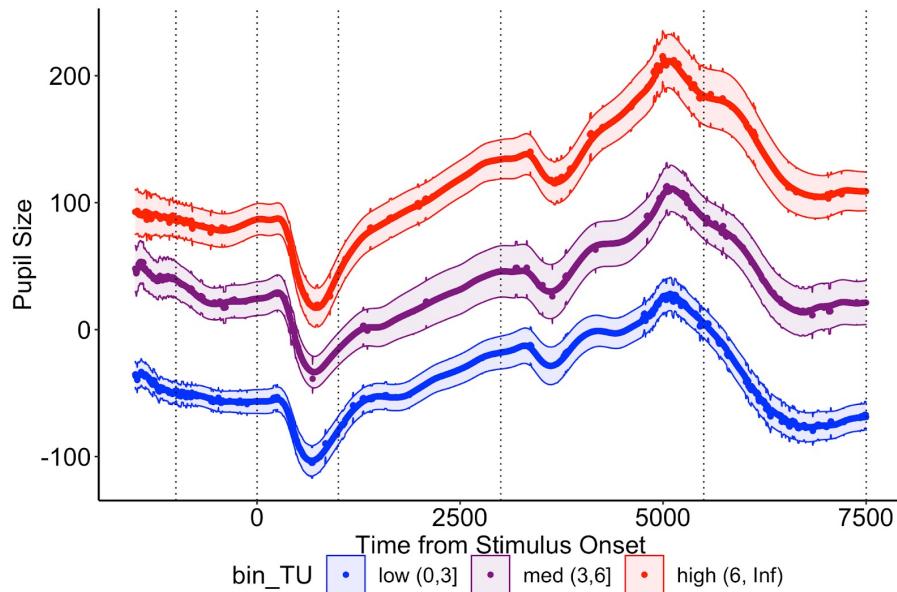
Trial Baseline Pupil Size_t =

|Relative Uncertainty_t| +

|Relative Value_t| / Total Uncertainty_t +

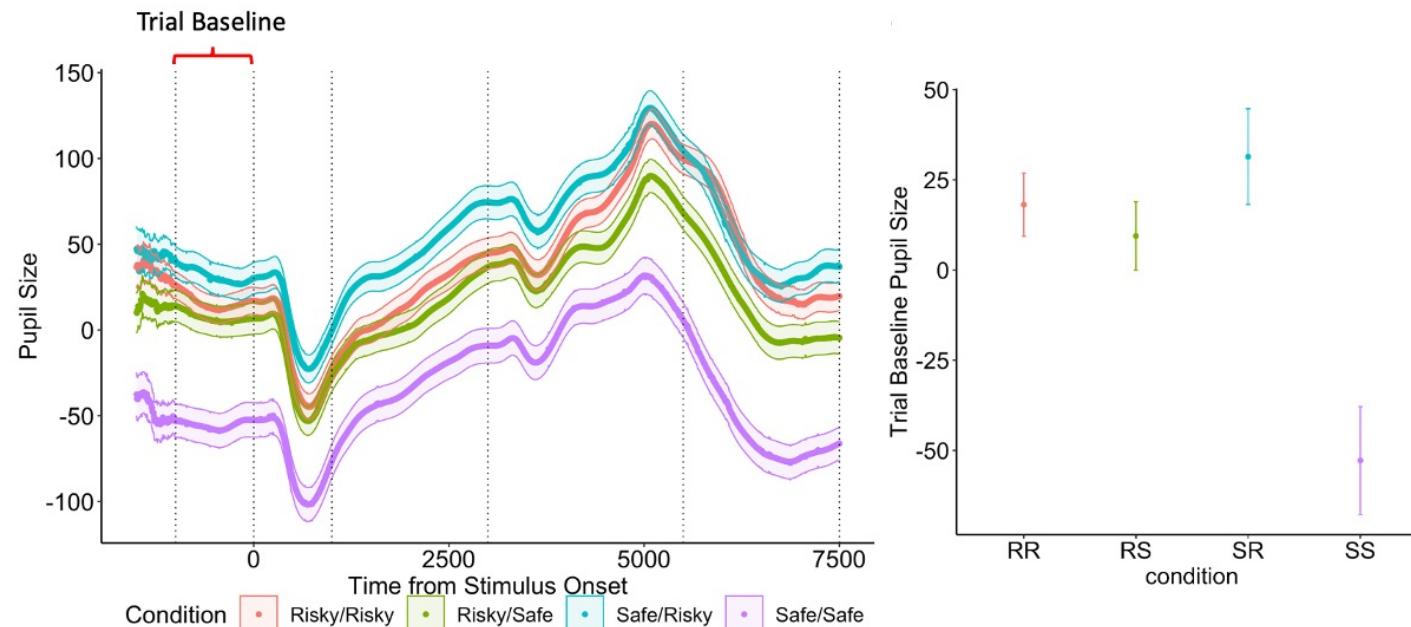
|Relative Value_t| + **Total Uncertainty_t**

Higher total uncertainty is associated with larger pupil size during the trial baseline.



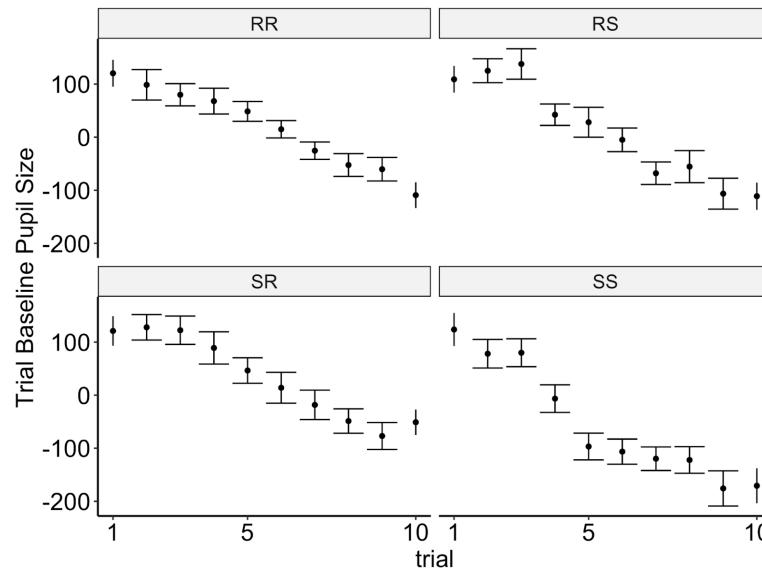
Pupil size encodes total uncertainty

Prediction: If pupil size encodes total uncertainty, average baseline pupil size should be smallest in Safe/Safe condition.



Pupil size encodes total uncertainty

Prediction: If pupil size encodes total uncertainty, pupil size should gradually decrease within a block, as people gain more experience with the same pair of slot machines.



Pupil size encodes total uncertainty both in within-block and between-block levels.

$N = 48$, Error bar = 1 SE

RR: Risky/Risky, RS: Risky/Safe, SR: Safe/Risky, SS: Safe/Safe

Decoding analysis: Augment the choice model with total uncertainty decoded from the pupil model

Prediction: If pupil size encodes total uncertainty & people uses the encoded total uncertainty to guide exploration, adding the decoded total uncertainty to the choice model will improve the behavior model fit.



Decoded Total Uncertainty_t =

|Relative Uncertainty_t| +

|Relative Value_t| / Total Uncertainty_t +

|Relative Value_t| - Trial Baseline Pupil Size_t



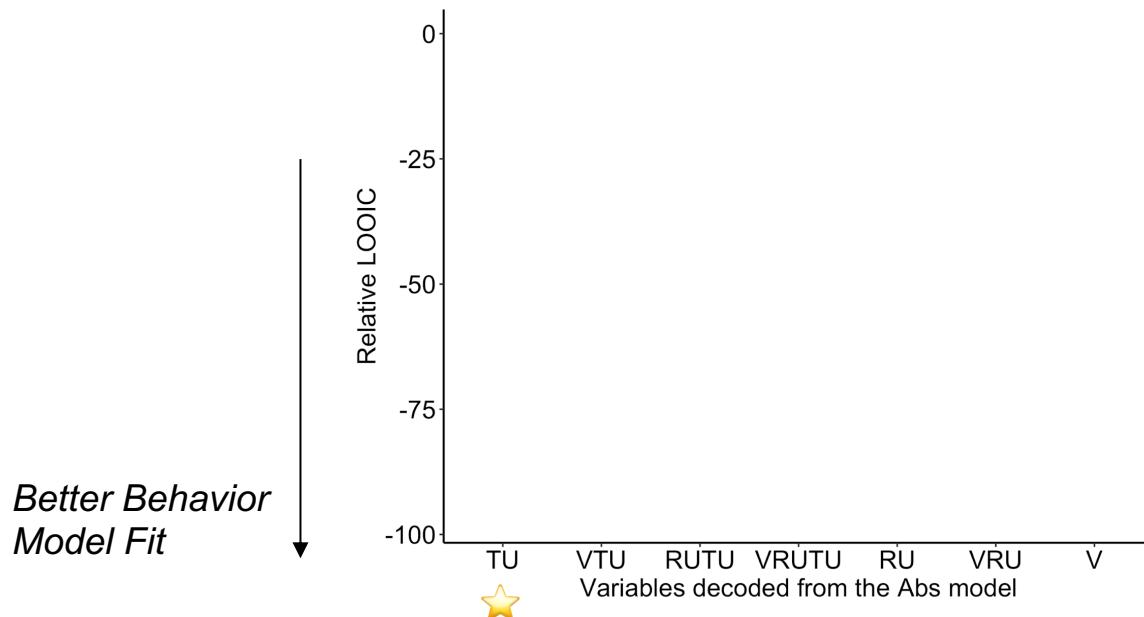
P (choosing left) =

$\Phi(w_1 \text{ Relative Uncertainty}_t +$

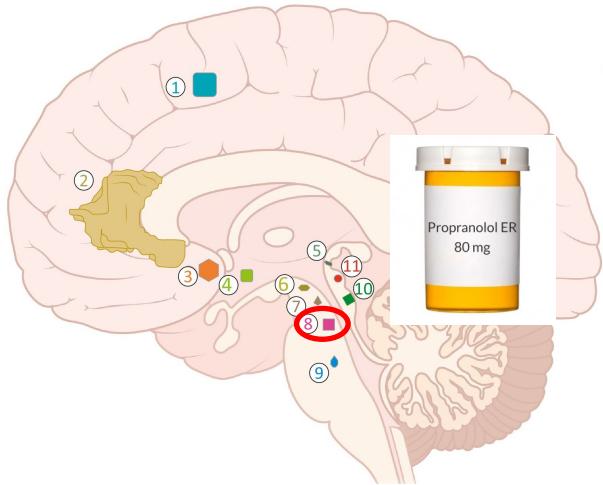
$w_2 \text{ Relative Value}_t / \text{Total Uncertainty}_t +$

$w_3 \text{ Relative Value}_t + w_4 \text{ Relative Value}_t / \text{decoded Total Uncertainty}_t)$

Decoding analysis: Augment the choice model with total uncertainty decoded from the pupil model



The choice model augmented with total uncertainty (decoded from the pupil model) improve the choice model's model fit.



?

- Directed
- Random
- Value-driven



- Pupil size encodes total uncertainty in the environment, which is subsequently used in guiding random exploration.
- Under the assumption that pupil size is a proxy of LC-NE activity, these results extend the theory of LC-NE function in exploration, highlighting its selective role in driving uncertainty-guided random exploration.

Thank you!



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Questions?



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