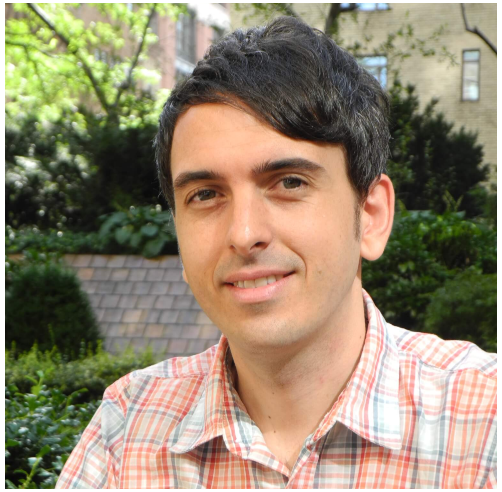
Introspective inference counteracts perceptual distortion

06/25/2023

Andra Mihali, Marianne Broeker, Florian Ragalmuto and Guillermo Horga





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Abstract

Introspective agents can recognize the extent to which their internal perceptual experiences deviate from the actual states of the external world. This ability, also known as insight, is critically required for reality testing and is impaired in psychosis, yet very little is known about its cognitive underpinnings. We developed a Bayesian modeling framework and a novel psychophysics paradigm to quantitatively characterize this type of insight while participants experienced a motion after-effect illusion. Participants could compensate for the illusion when

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Introspective inference counteracts perceptual distortion

Quantitative *measure* and candidate *process model* for **insight** with relevance to psychiatry (computational psychiatry)

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Hallucinations
Illusions

New York State Psychiatric Institute

Columbia University Department of Psychiatry

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Quantitative *measure* and candidate *process model* for **insight** with relevance to psychiatry (computational psychiatry)

Hallucinations

Illusions

Perceptual insight

Operationalization

- The ability to incorporate introspective knowledge about distortions in internal percepts to effectively infer the actual state of the external world

Experimental test

- Inducing perceptual distortion and probing compensation… through Motion after-effect (MAE)

Insight

the ability to incorporate introspective
knowledge about distortions in internal percepts
to effectively infer the actual state
of the external world

BJPsych | The British Journal of Psychiatry (2020) 217, 521–523. doi: 10.1192/bjp.2019.217

Analysis

Insight and psychosis: the next 30 years

Anthony S. David

JAMA Network Insights

Working With Patients With Impaired Insight

Hannah E. Brown, MD; Sydney Feinstein, BA; David C. Henderson, MD

no objective measures
or process models

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Visual metacognition

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the ability for one's subjective sense of confidence to track the objective accuracy

several objective measures and process models

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2021, Vol. 76, No. 9, 1445–1453
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Visual Metacognition: Measures, Models, and Neural Correlates

Dobromir Rahnev
School of Psychology, Georgia Institute of Technology

PLOS | COMPUTATIONAL BIOLOGY

RESEARCH ARTICLE

Comparing Bayesian and non-Bayesian accounts of human confidence reports

William T. Adler[1]*, Wei Ji Ma[1,2]

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Review article

Perceptual reality monitoring: Neural mechanisms dissociating imagination from reality

Nadine Dijkstra[a,*], Peter Kok[a], Stephen M. Fleming[a,b,c]

[a] Wellcome Centre for Human Neuroimaging, University College London, United Kingdom
[b] Max Planck UCL Centre for Computational Psychiatry and Aging Research, University College London, United Kingdom
[c] Department of Experimental Psychology, University College London, United Kingdom

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Neuroscience and Biobehavioral Reviews

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ELSEVIER

Systematic review and meta-analysis of metacognitive abilities in individuals with schizophrenia spectrum disorders

Martin Rouy[a,*], Pauline Saliou[a], Ladislas Nalborczyk[b], Michael Pereira[a], Paul Roux[c,1], Nathan Faivre[a,1]

Perceptual insight

Operationalization

- The ability to incorporate introspective knowledge about distortions in internal percepts to effectively infer the actual state of the external world

Experimental test

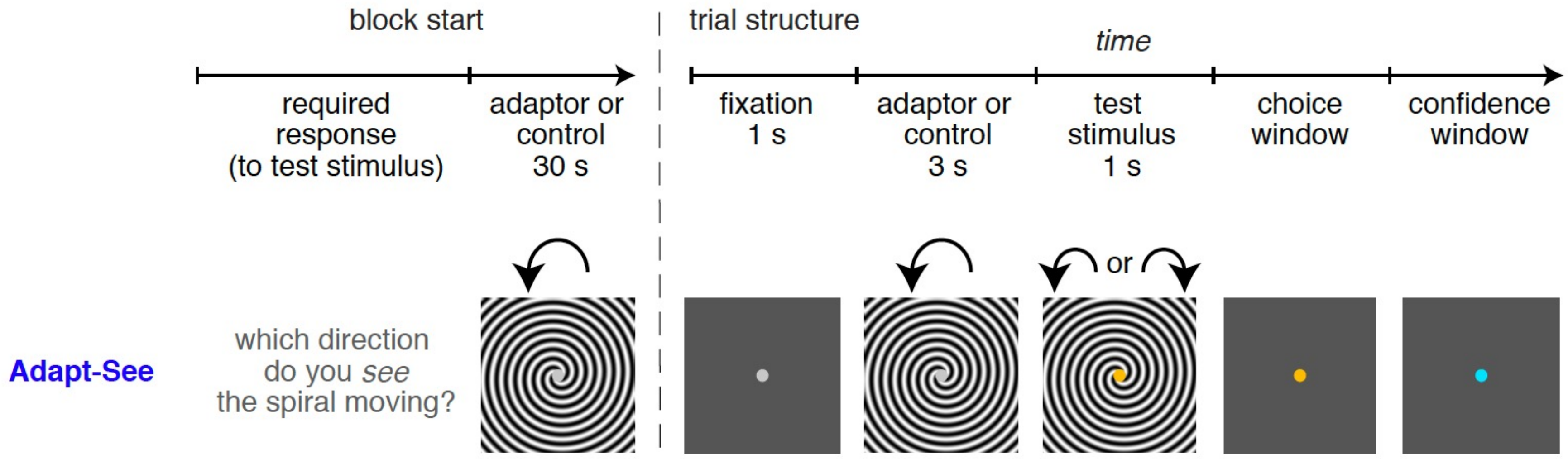
- Inducing perceptual distortion and probing compensation… through Motion after-effect (MAE)

Approach: Motion after-effect illusion

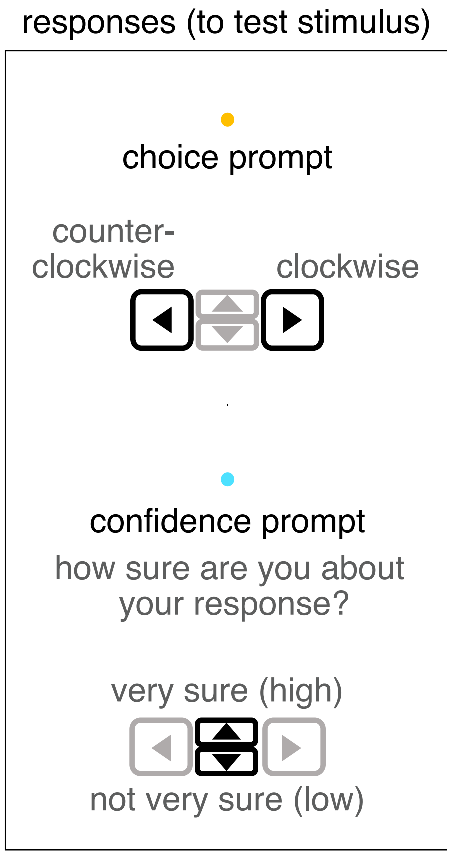
Implementation of Archimedean spiral adapted from Peter Scarfe
https://peterscarfe.com/spiraltexturedemo.html

Adaptors with complex motion yield stronger MAE *Bex et al, 1999*
Spiral after-effect *Pickersgill and Jeeves, 1958, Herrington and Claridge, 1965, Cavanaugh and Favreau, 1980, Kaunitz et al, 2011*

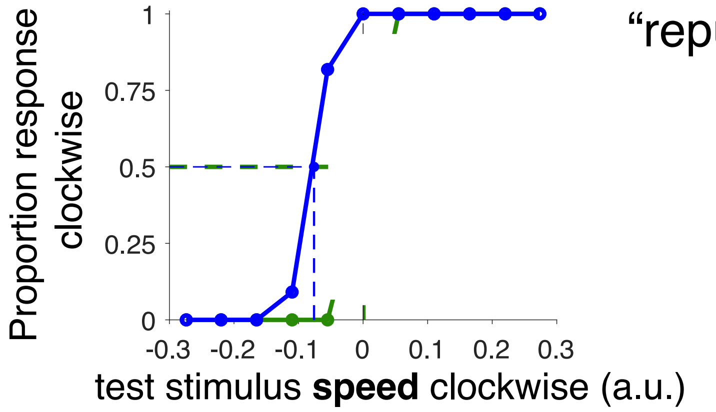
Task



Clifford and Rhodes, 2005,
Witthoft et al, 2018



How to measure the MAE strength / perceptual distortion?



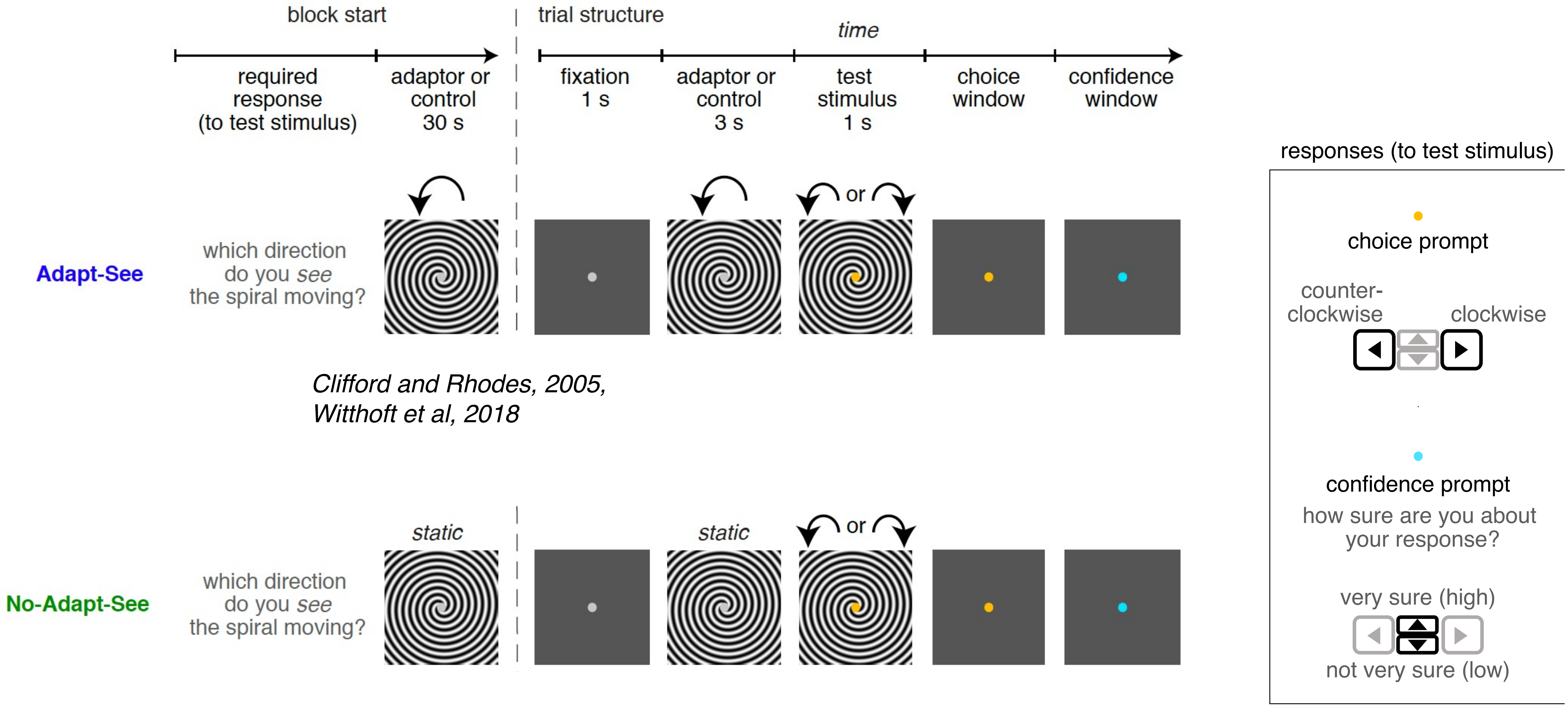
“repulsion effect” of adaptation

Levinson and Sekuler, 1976

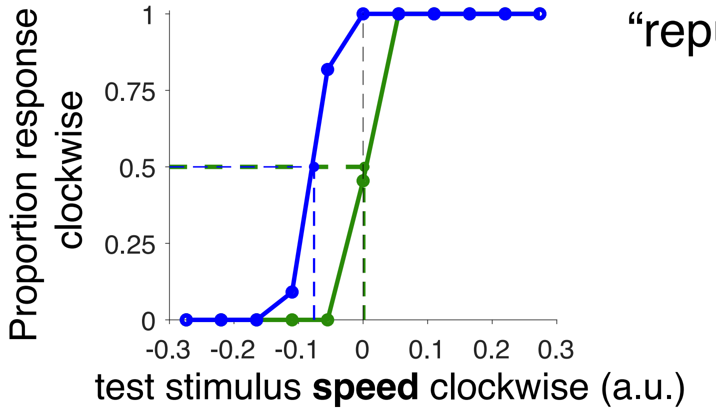
Implicit nulling method

Blake and Hiris, 1993
Castet et al, 2002
Thakkar et al, 2018, 2019

Task


block start
trial structure
time
required response (to test stimulus)
adaptor or control 30 s
fixation 1 s
adaptor or control 3 s
test stimulus 1 s
choice window
confidence window
or
Adapt-See
which direction do you *see* the spiral moving?
Clifford and Rhodes, 2005, Witthoft et al, 2018
static
static
or
No-Adapt-See
which direction do you *see* the spiral moving?
responses (to test stimulus)
choice prompt
counter-clockwise
clockwise
confidence prompt
how sure are you about your response?
very sure (high)
not very sure (low)

How to measure the MAE strength / perceptual distortion?



“repulsion effect” of adaptation

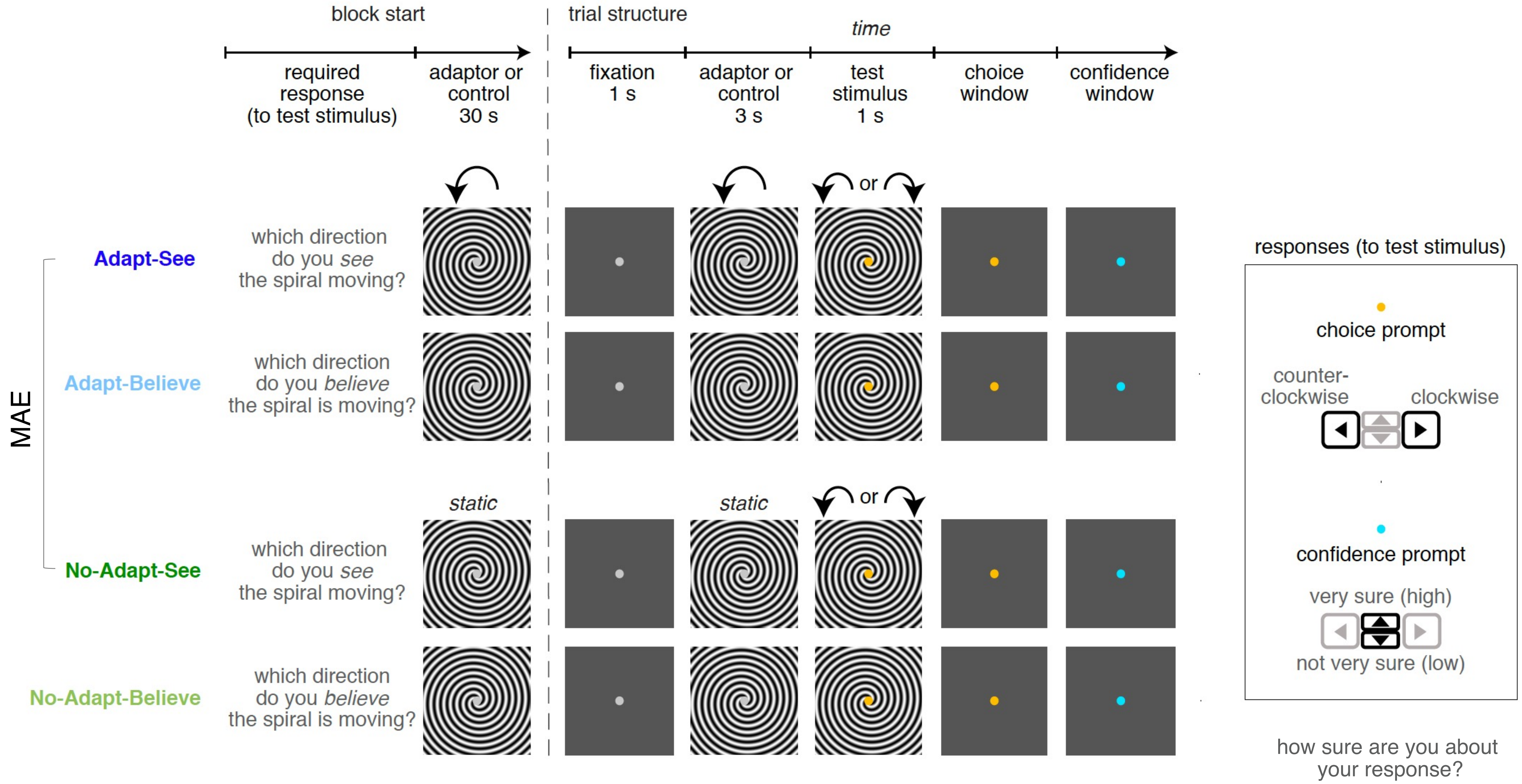
Levinson and Sekuler, 1976

Implicit nulling method

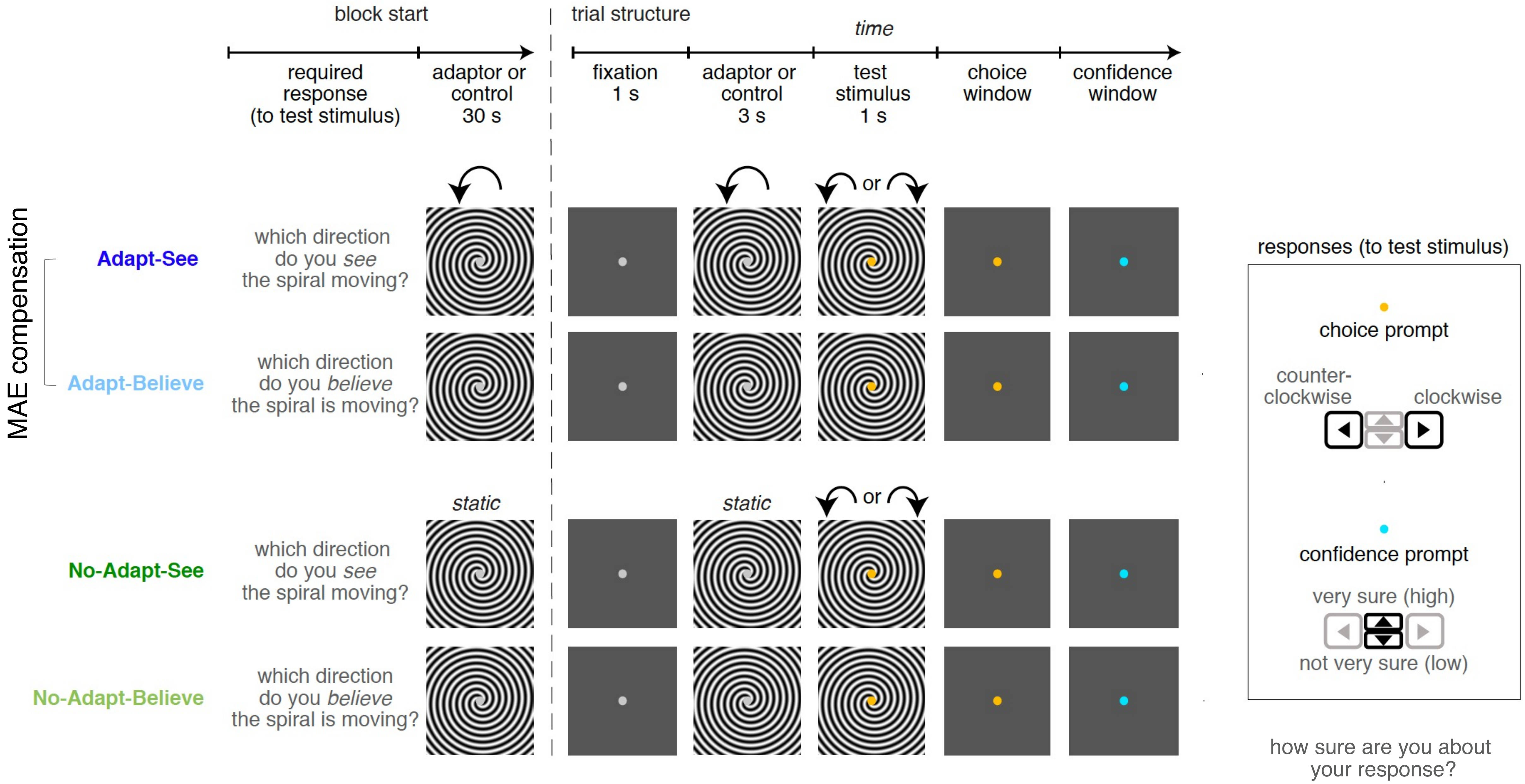
Blake and Hiris, 1993
Castet et al, 2002
Thakkar et al, 2018, 2019

$$\boxed{\text{MAE} = \mu_{\text{Adapt-See}} - \mu_{\text{No-Adapt-See}}}$$

Task design


block start
trial structure
time
required response (to test stimulus)
adaptor or control 30 s
fixation 1 s
adaptor or control 3 s
test stimulus 1 s
choice window
confidence window
or
static
MAE
Adapt-See
which direction do you *see* the spiral moving?
Adapt-Believe
which direction do you *believe* the spiral is moving?
No-Adapt-See
which direction do you *see* the spiral moving?
No-Adapt-Believe
which direction do you *believe* the spiral is moving?
responses (to test stimulus)
choice prompt
counter-clockwise
clockwise
confidence prompt
very sure (high)
not very sure (low)
how sure are you about your response?

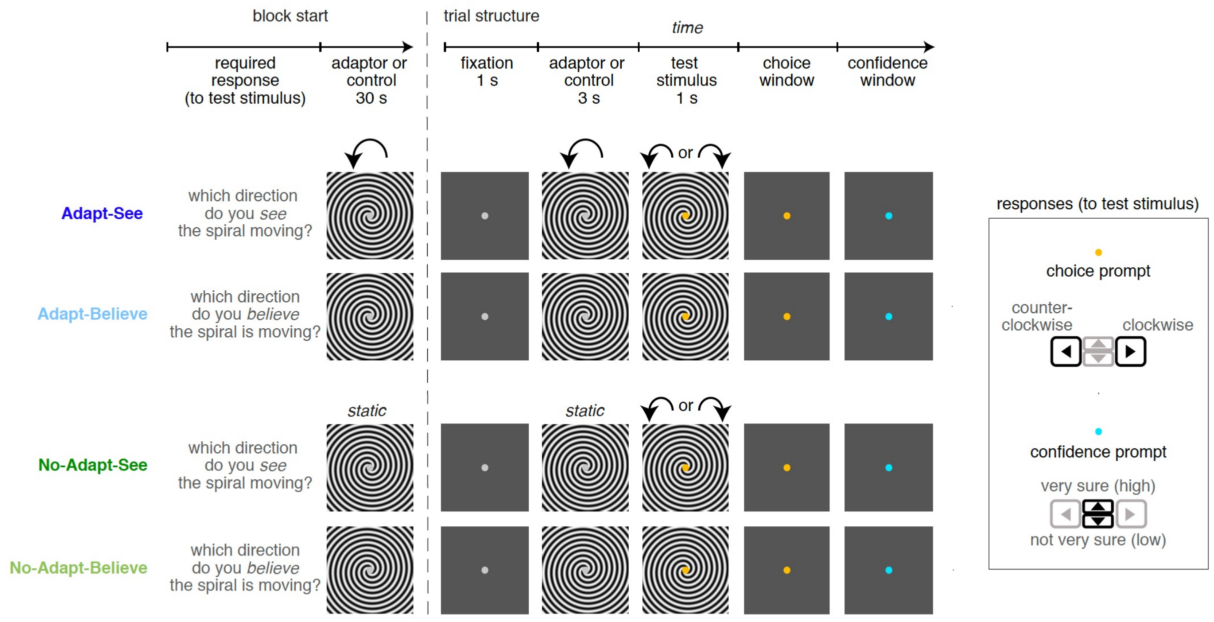
Task design


block start
trial structure
time
required response (to test stimulus)
adaptor or control 30 s
fixation 1 s
adaptor or control 3 s
test stimulus 1 s
choice window
confidence window
or
static
MAE compensation
Adapt-See
which direction do you *see* the spiral moving?
Adapt-Believe
which direction do you *believe* the spiral is moving?
No-Adapt-See
which direction do you *see* the spiral moving?
No-Adapt-Believe
which direction do you *believe* the spiral is moving?
responses (to test stimulus)
choice prompt
counter-clockwise
clockwise
confidence prompt
very sure (high)
not very sure (low)
how sure are you about your response?

Task outline

- Extensive training on the illusion and task components + quizzes

- 2 blocks of Adapt-See
- 2 blocks of Adapt-Believe
- 2 blocks of No-Adapt-See
- 2 blocks of No-Adapt-Believe



Adapt-Believe condition training

Adaptor Spiral 1 speed ←

Illusion →

Test Spiral 2 speed ←

See →

Adapt-Believe condition training

Adaptor Spiral 1 speed ⟵

Illusion ⟶

Test Spiral 2 speed ←

See → Right

Adapt-Believe condition training

Adaptor Spiral 1 speed ←——

Illusion ——→

Test Spiral 2 speed ← **Believe**

See → Right

Adapt-Believe condition training

Adaptor Spiral 1 speed ⟵

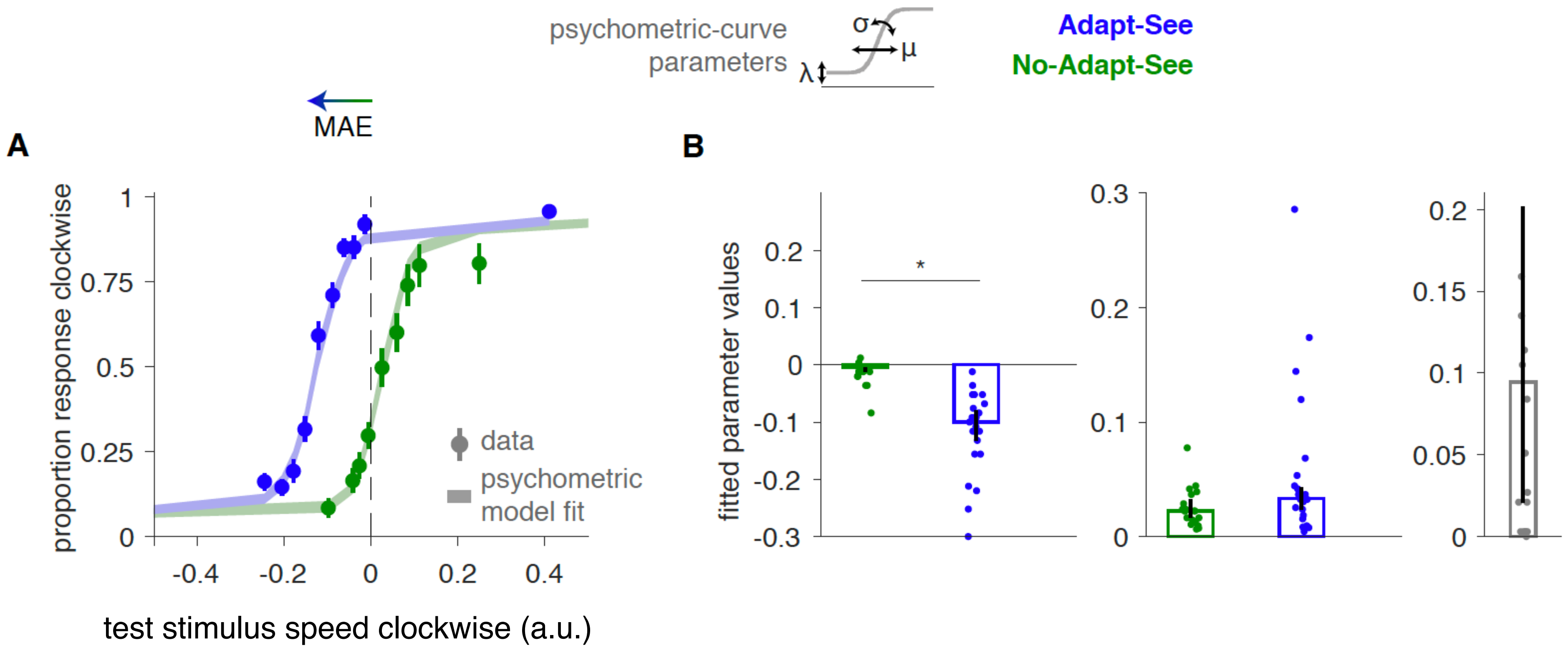
Illusion ⟶

Test Spiral 2 speed ← **Believe** Left ↑

See → Right

Results Adapt-See: MAE can induce a perceptual distortion (offset)

Experiment 1



N = 22 participants

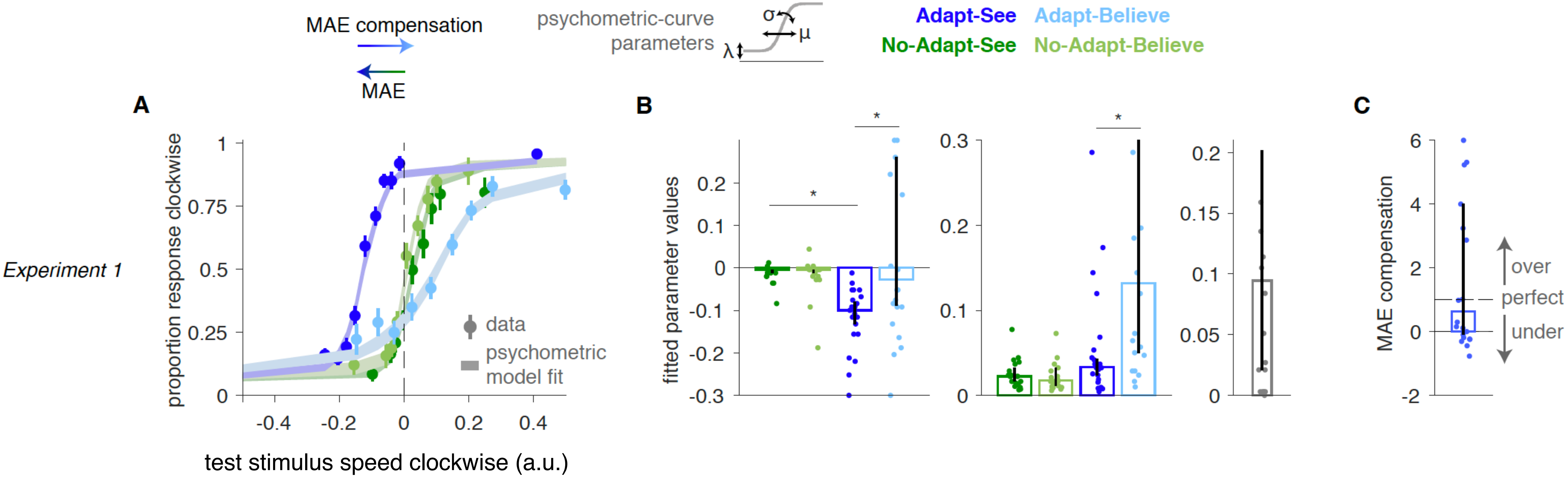
bias μ

noise σ

lapse λ

test stimulus speed clockwise (a.u.)

Participants can compensate for perceptual distortions



$$\text{MAE compensation} = \frac{\mu_{\text{Adapt-Believe}} - \mu_{\text{Adapt-See}}}{|\mu_{\text{Adapt-See}}|}$$

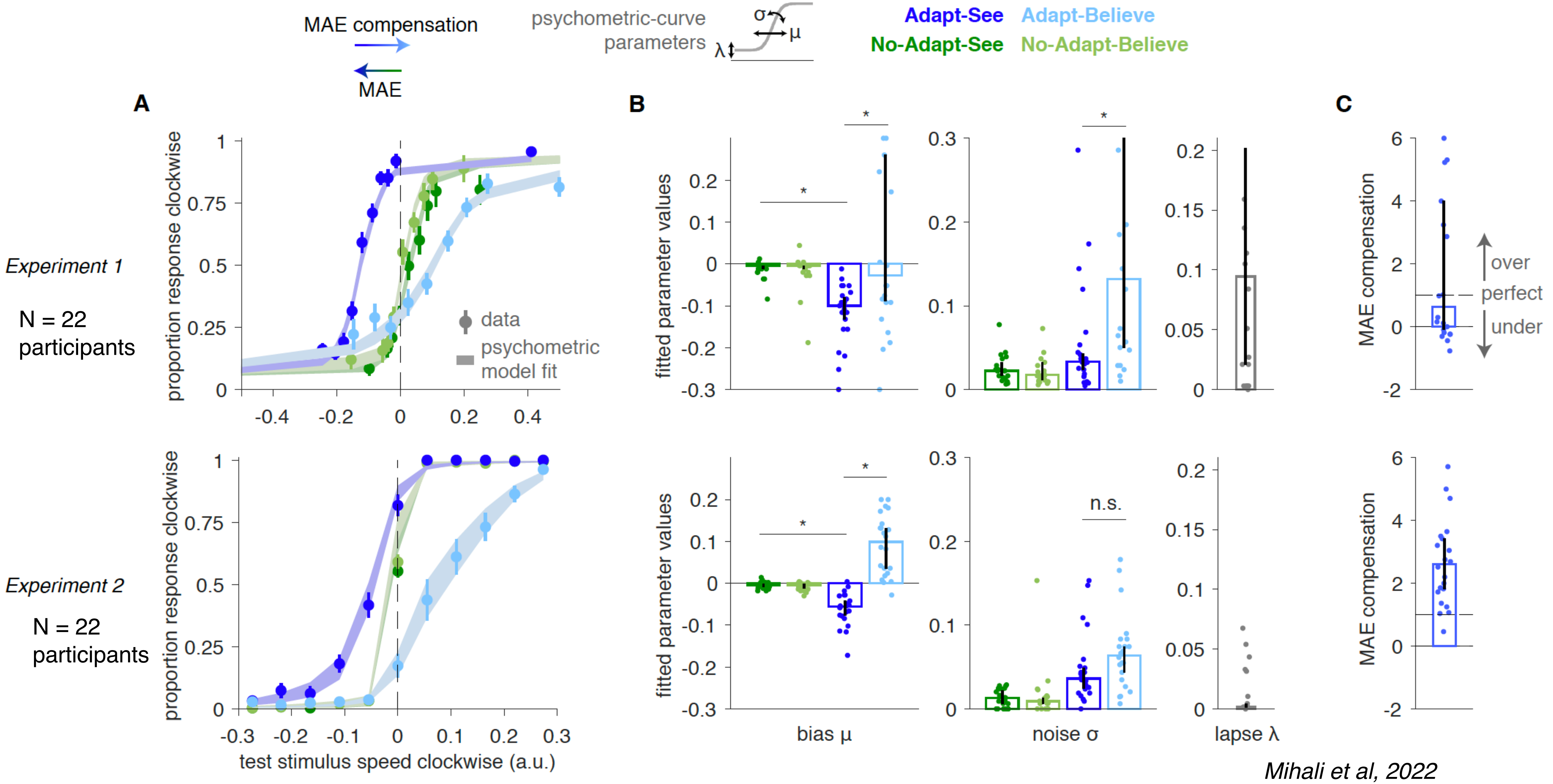
bias μ

noise σ

lapse λ

test stimulus speed clockwise (a.u.)

Participants can (over)compensate for perceptual distortions



Mihali et al, 2022

Healthy controls can compensate for the MAE, but is this *true insight?*

Is this compensation at an intermediate perceptual inference level?

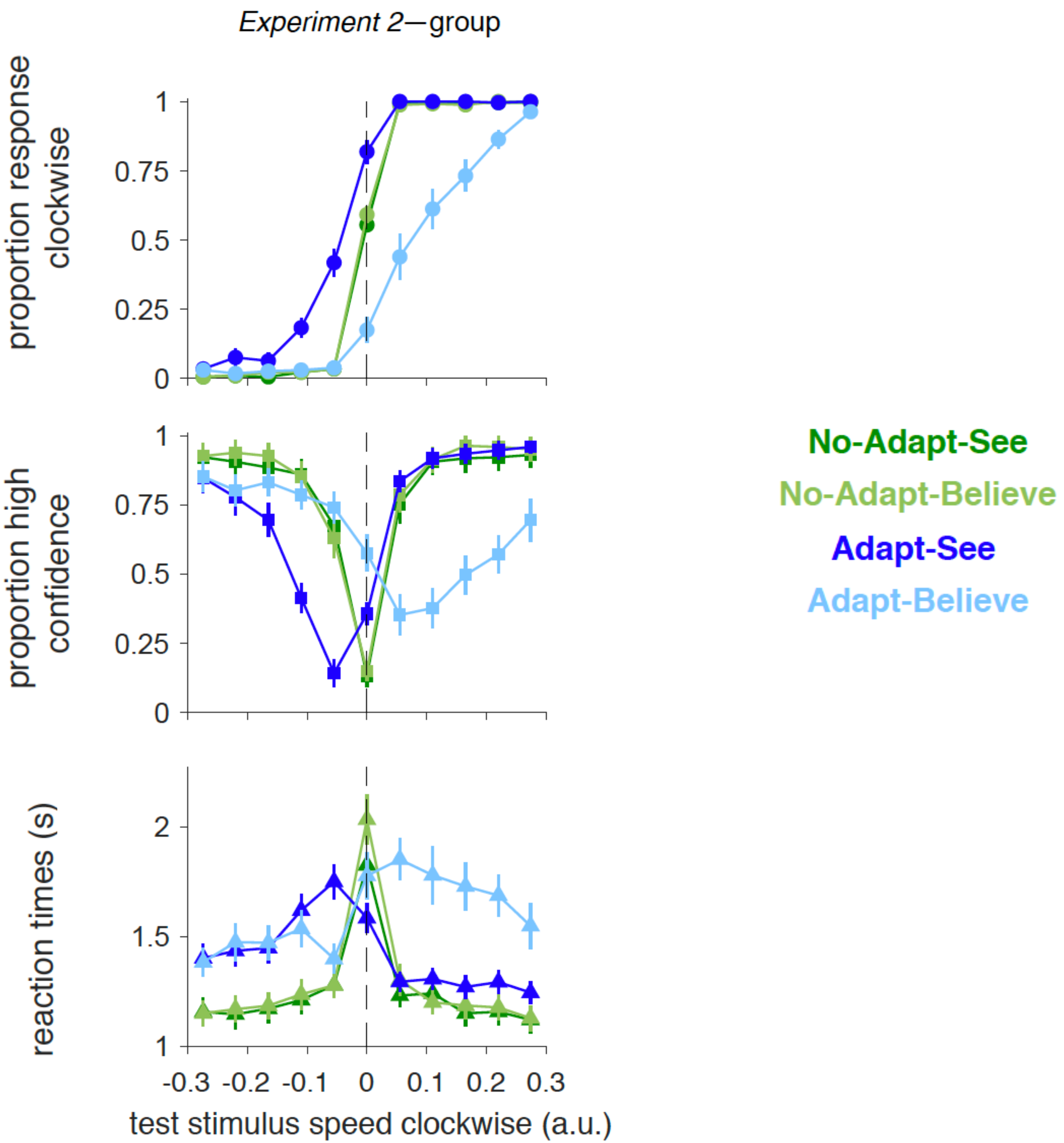
Healthy controls can compensate for the MAE, but is this *true insight?*

Is this compensation at an intermediate perceptual inference (and not a late response) level?

To gain clarity, we also looked at participants' confidence reports.

Maldonado Moscoso et al., *Proc R Soc B* 2020;
Gallagher et al., *Sci Rep* 2019

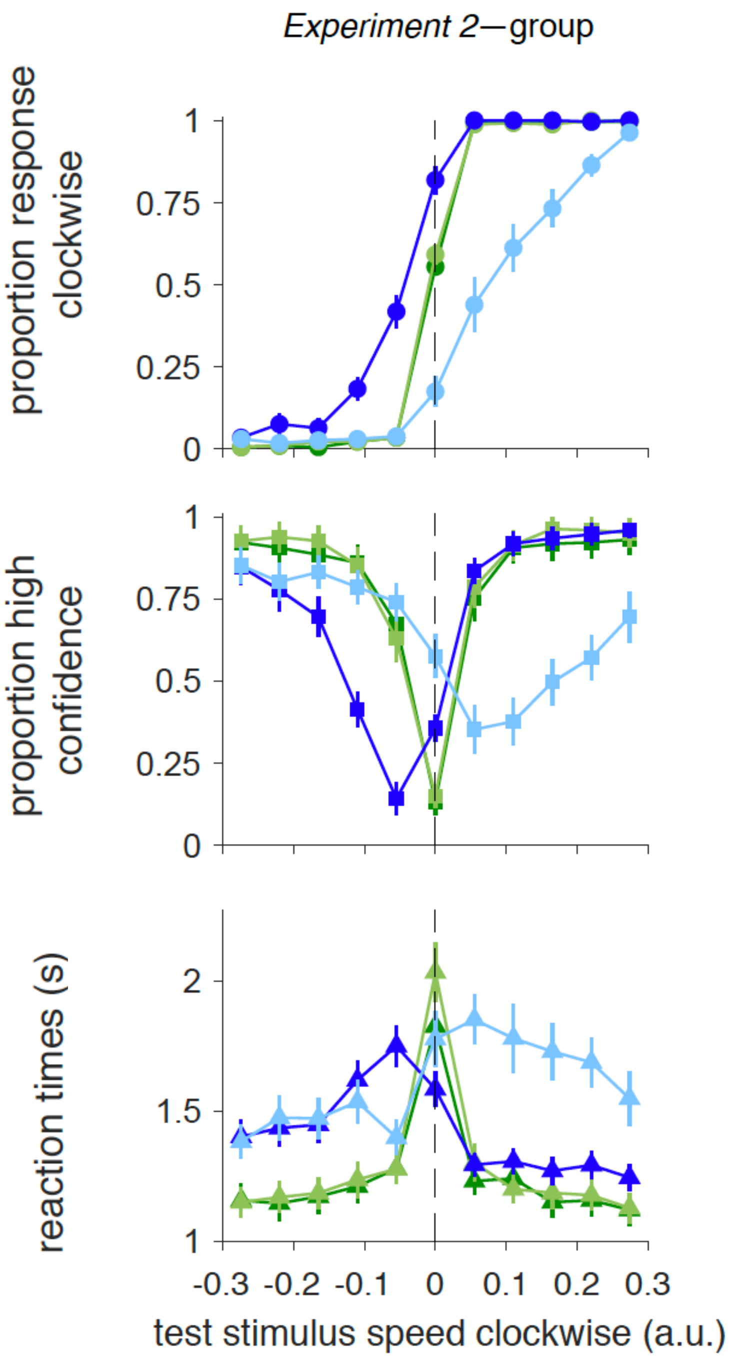
Psychometric curves for **MAE and MAE compensation** shift in tandem with confidence and RT curves



Psychometric curves for **MAE and MAE compensation** shift in tandem with confidence and RT curves

Bayesian process models of confidence

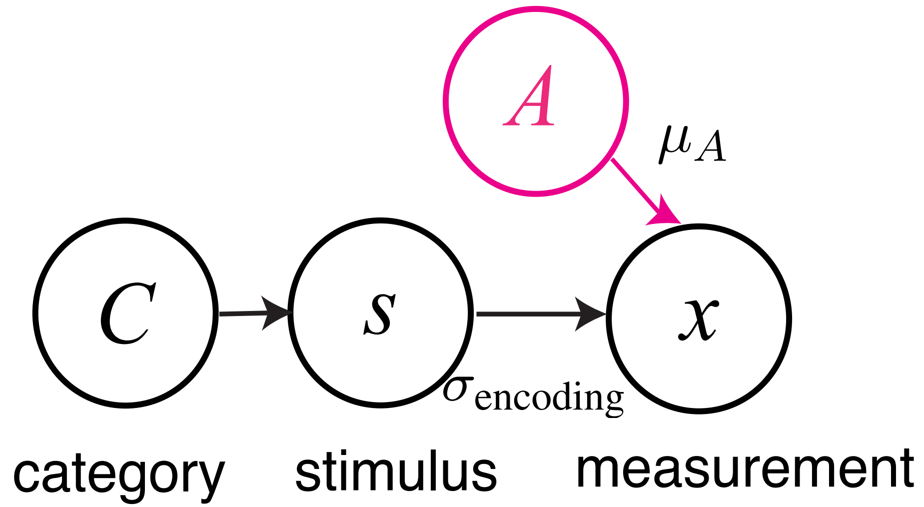
Green and Swets, 1966
Knill and Pouget, 2004,
Kording and Wolpert, 2006,
Adler and Ma, 2018
Hsin and Ma, 2019



No-Adapt-See
No-Adapt-Believe
Adapt-See
Adapt-Believe

Bayesian model of perceptual insight

generative model

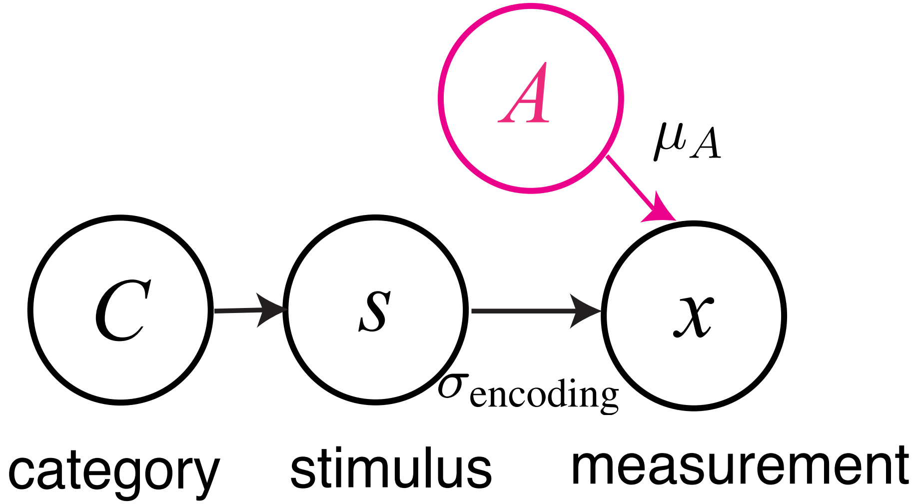


Left / right

Green and Swets, 1966
Knill and Pouget, 2004,
Kording and Wolpert, 2006,
Adler and Ma, 2018
Hsin and Ma, 2019
Mihali et al, 2022

Bayesian model of perceptual insight

generative model

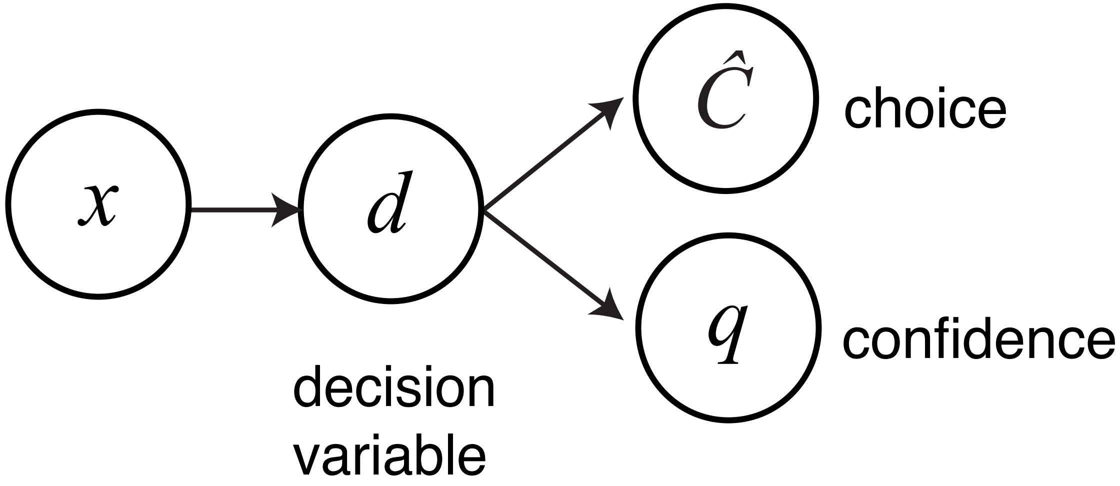


Left / right

inference

d = log prior ratio + LLR

LLR = f(x, $\mu_{\text{likelihood}}$, σ_{encoding})



Green and Swets, 1966
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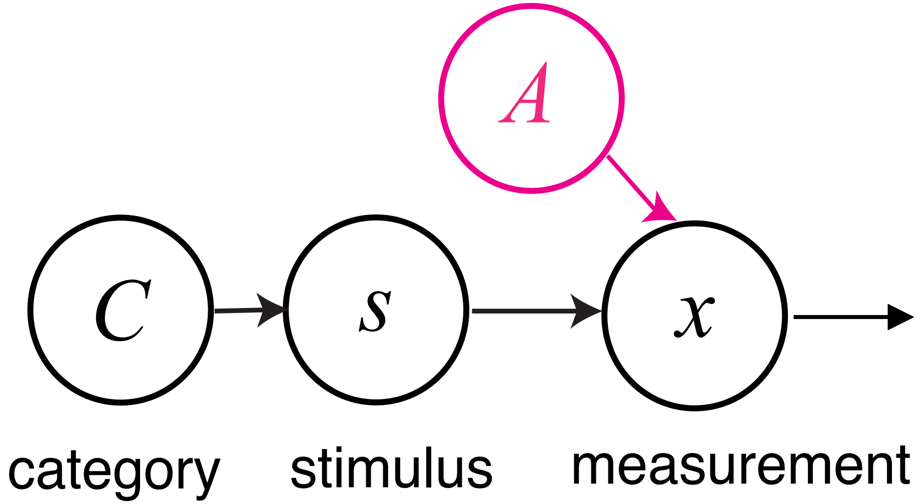
Mihali et al, 2022

Bayesian model of perceptual insight

generative model



inference

d = log prior ratio + LLR

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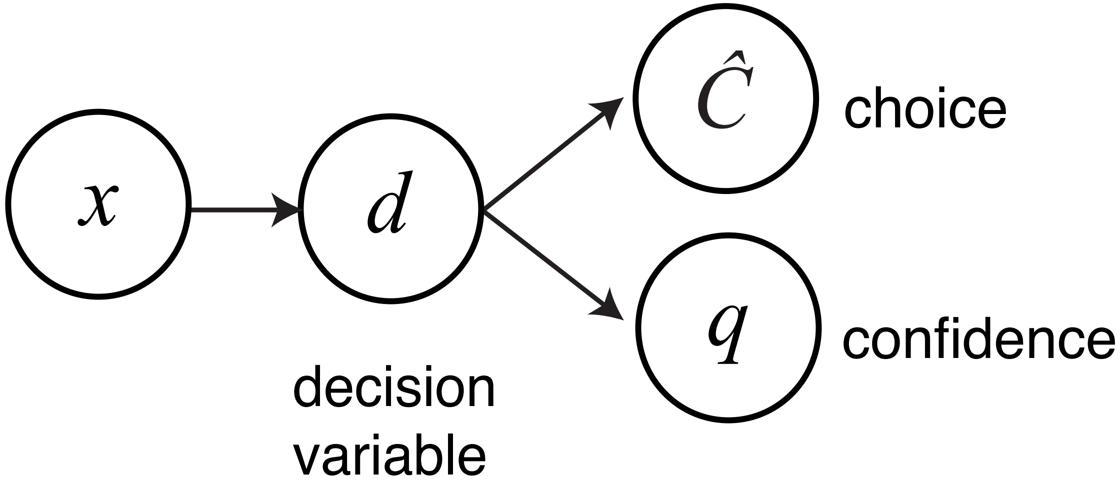


$$p(C=1|x) = \frac{1}{1+e^{-d}}$$

$$\hat{C} = \underset{C}{\operatorname{argmax}}\, p(C|x)$$

$$\text{confidence} = p(C=\hat{C}|x) = \frac{1}{1+e^{|d|}}$$

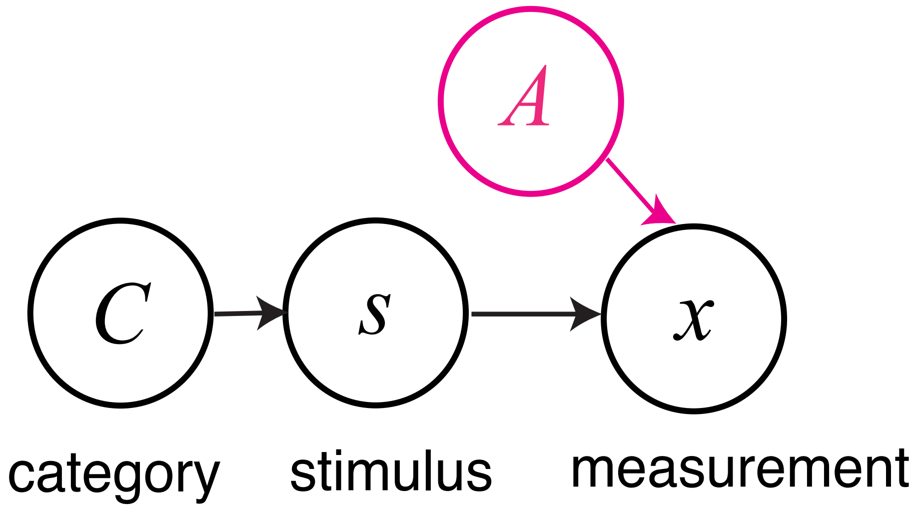
$$q = \begin{cases} 1, & \text{if confidence} > k_{\text{confidence}} \\ 0, & \text{otherwise} \end{cases}$$

Green and Swets, 1966
Knill and Pouget, 2004,
Kording and Wolpert, 2006,
Adler and Ma, 2018
Hsin and Ma, 2019
Mihali et al, 2022

Bayesian model of perceptual insight

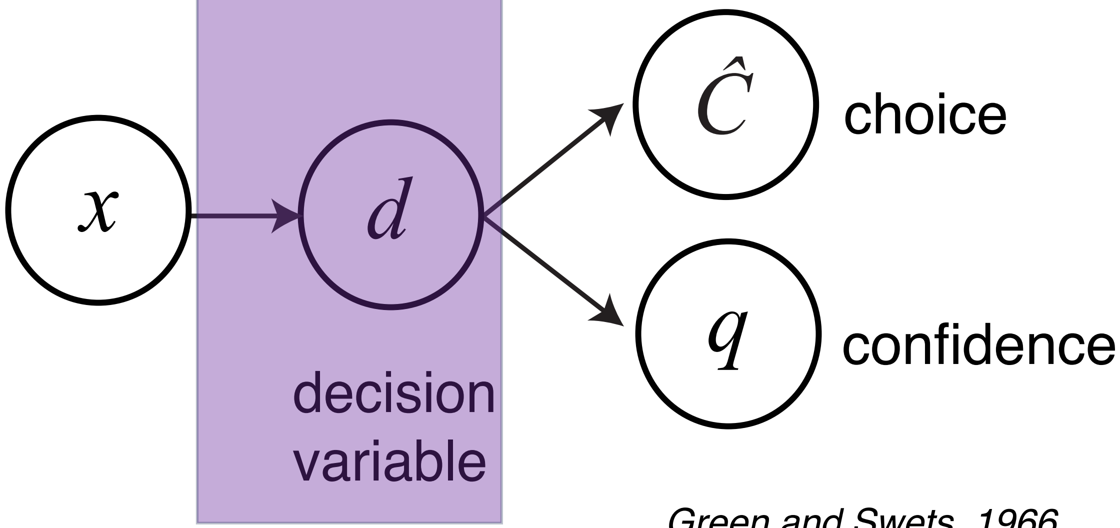
intermediate

generative model



inference

d = log prior ratio + LLR
LLR = f(x, $\mu_{\text{likelihood}}$, σ_{encoding})



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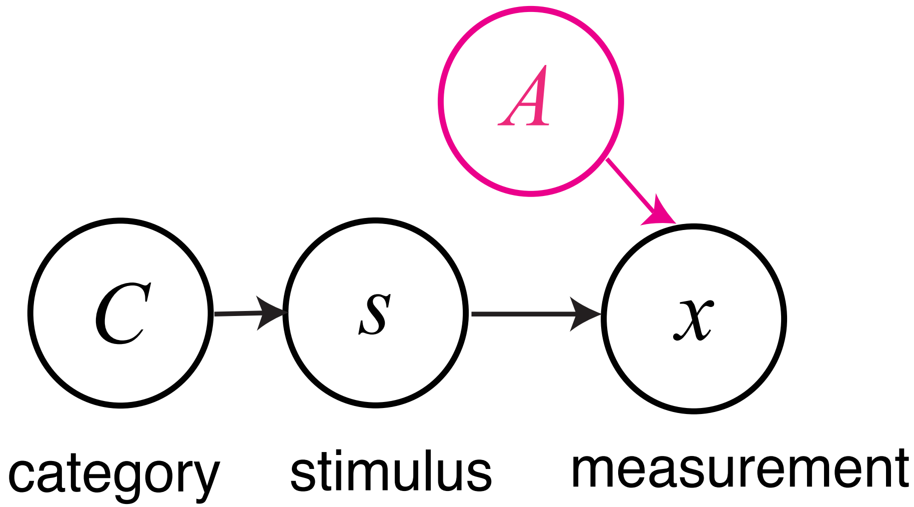
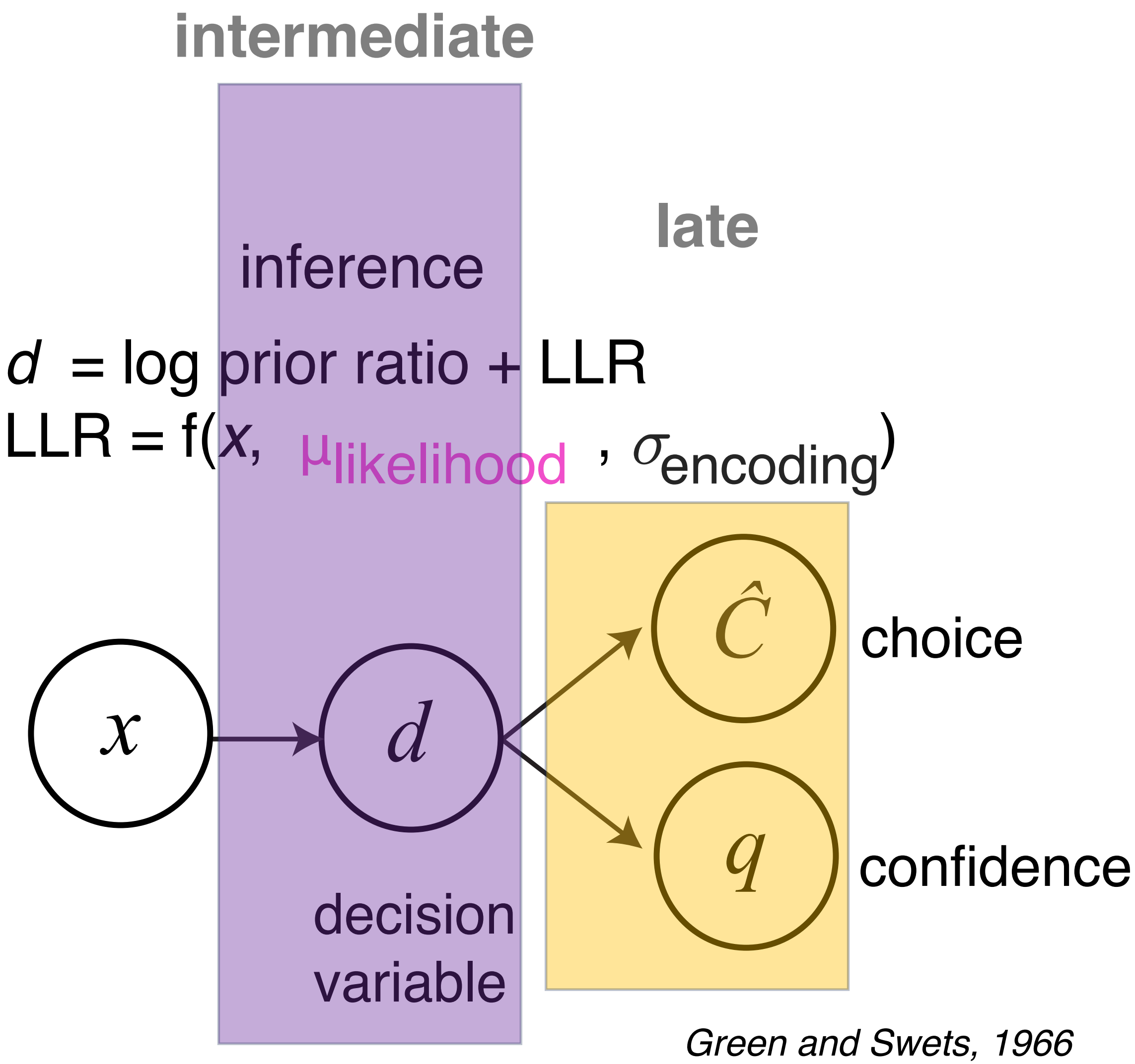
Bayesian model of perceptual insight

generative model





$$
\begin{aligned}
p(C=1|x) &= \frac{1}{1+e^{-d}} \\
\hat{C} &= \operatorname*{argmax}_{C} p(C|x)
\end{aligned}
$$

$$
\text{confidence} = p(C=\hat{C}|x) = \frac{1}{1+e^{|d|}}
$$

$$
q = \begin{cases} 1, & \text{if confidence} > k_{\text{confidence}} \\ 0, & \text{otherwise} \end{cases}
$$

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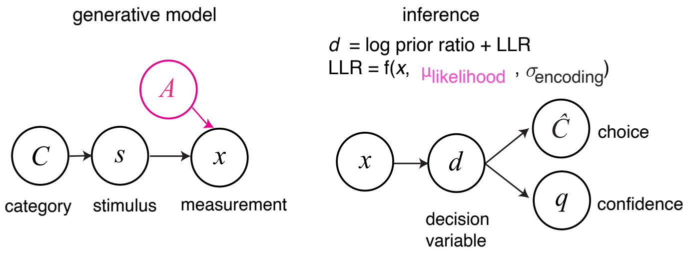
Knill and Pouget, 2004,
Kording and Wolpert, 2006,
Adler and Ma, 2018
Hsin and Ma, 2019
Mihali et al, 2022

Bayesian model of perceptual insight: model fits & model parameters

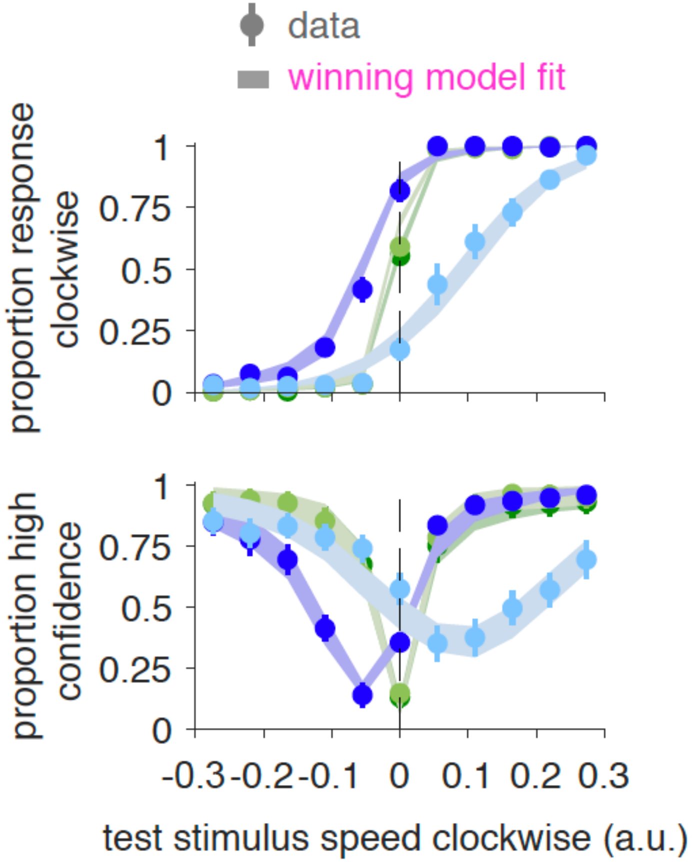


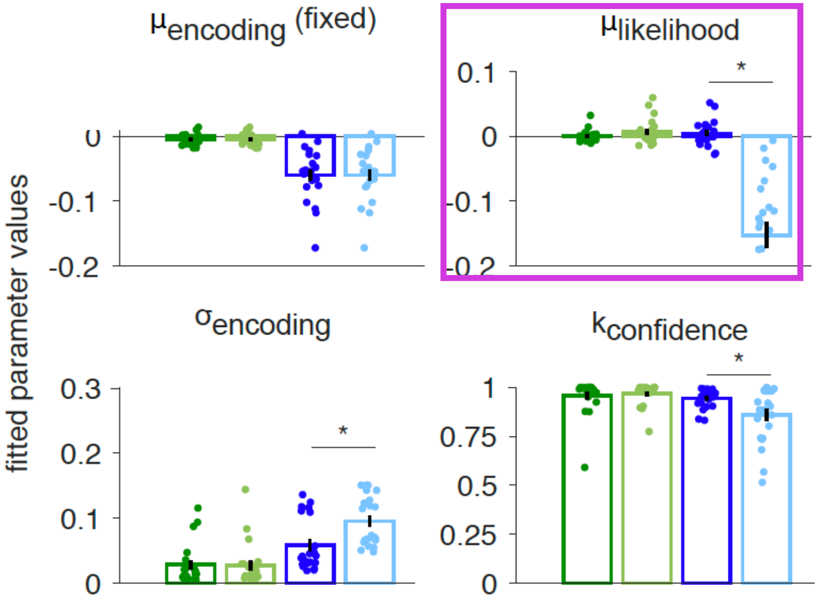
No-Adapt-See

No-Adapt-Believe

Adapt-See

Adapt-Believe





Conclusions

- People can experience perceptual distortions with the MAE illusion
- People with knowledge of the MAE illusion can (over)compensate for it
- A Bayesian inference model of perceptual insight with adjustments in the intermediate inference stage captured the data best and revealed differences in Adapt-See vs Adapt-Believe in a key parameter for perceptual insight, $\mu_{likelihood}$
- Healthy participants demonstrated perceptual insight, specifically the ability to **incorporate introspective knowledge about distortions** in internal percepts to effectively infer the actual state of the external world

Insight

the ability to incorporate introspective knowledge about distortions in internal percepts to effectively infer the actual state of the external world

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Dobromir Rahnev
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RESEARCH ARTICLE

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Acknowledgements

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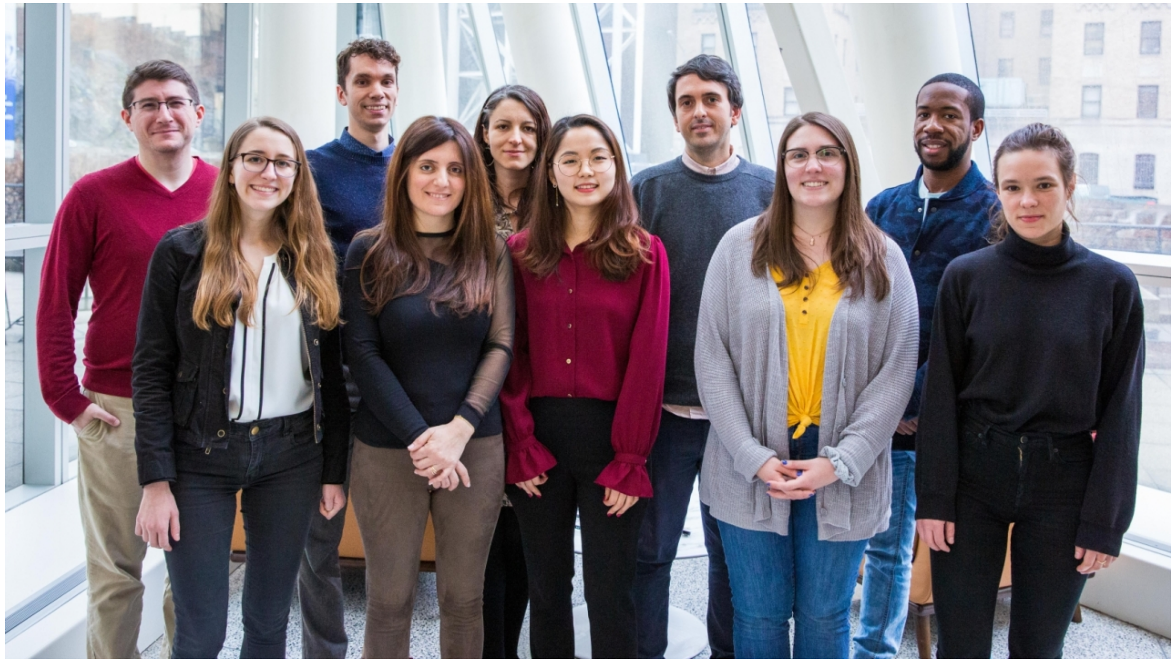
- Isabella Rosario
- Jocelyn Kim



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- Kyo Iigaya
- Daniel Wolpert
- Prady Sepulveda

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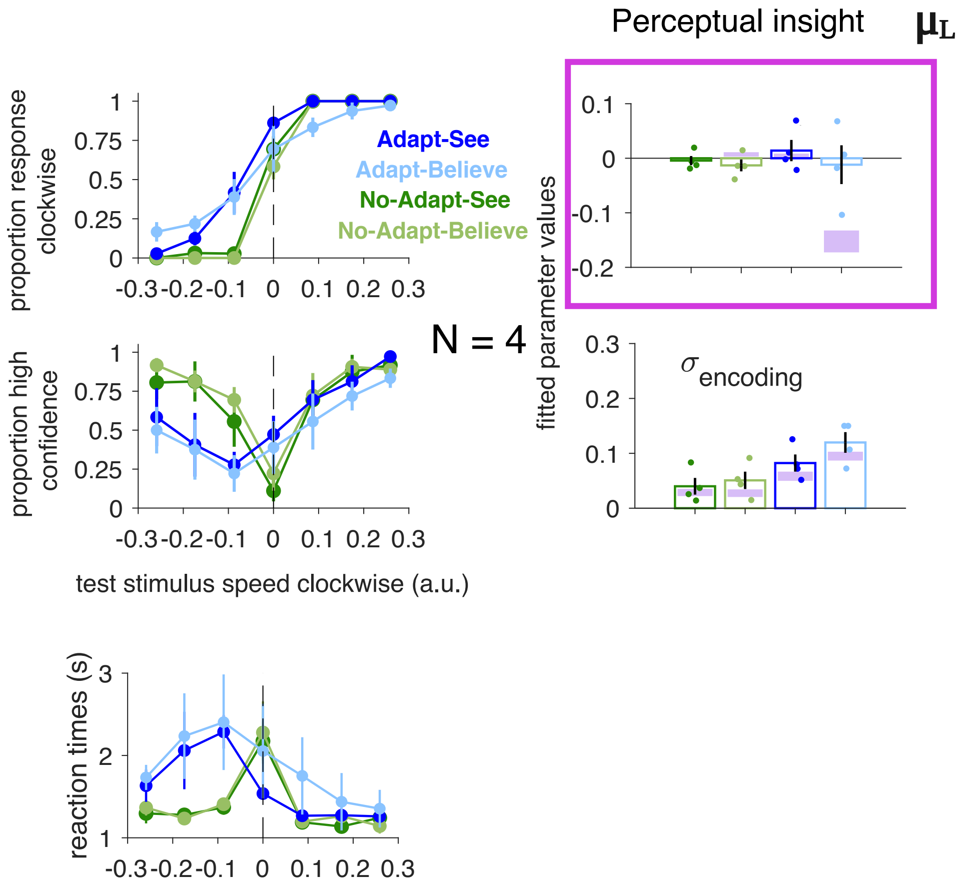
to Guillermo Horga

Thank you!

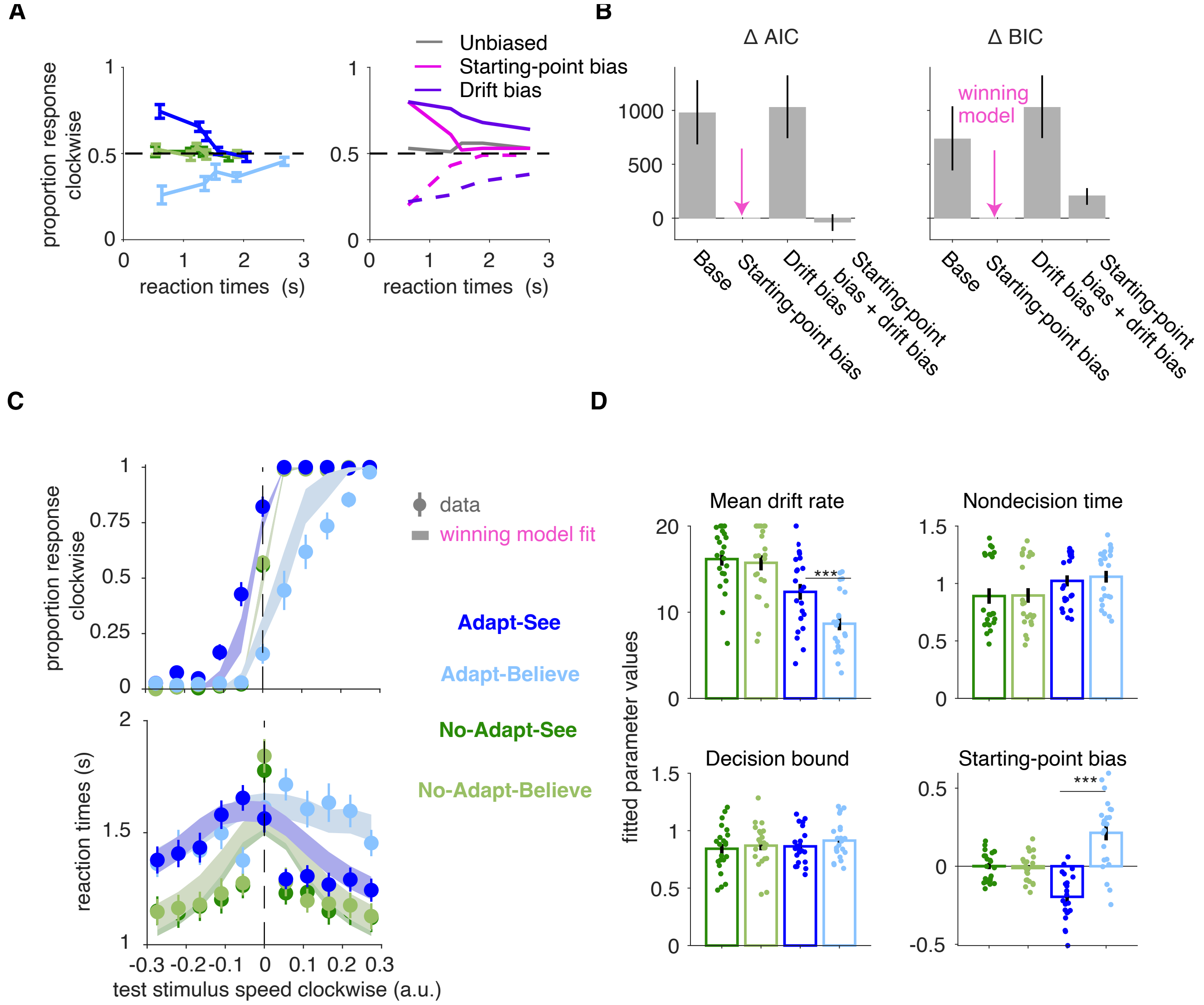
Is the perceptual insight parameter meaningful? / Can it capture insight impairments in psychosis?

Preliminary data in patients with psychosis: N = 4 Patients may have decreased perceptual insight



Mean pm sem from controls

DDM



A
proportion response clockwise
reaction times (s)
Unbiased
Starting-point bias
Drift bias
B
Δ AIC
Δ BIC
winning model
Base
Starting-point bias
Drift bias
Starting-point bias + drift bias
C
data
winning model fit
Adapt-See
Adapt-Believe
No-Adapt-See
No-Adapt-Believe
reaction times (s)
test stimulus speed clockwise (a.u.)
D
fitted parameter values
Mean drift rate
Nondecision time
Decision bound
Starting-point bias

Model fitting of the data from Experiment 2

Strategy and
parameters for the perceptual insight model

No Adapt	**Adapt**
No-Adapt-See	**Adapt-See**
No-Adapt-Believe	**Adapt-Believe**
1 μ_A (fixed, shared)	1 μ_A (fixed, shared)
2 σ	2 σ
2 μ_L	2 μ_L
2 $k_{\text{confidence}}$	2 $k_{\text{confidence}}$

14 parameters to fit total

Maximum likelihood estimation (MLE)

Model fitting of the data from Experiment 2

Strategy and parameters for the perceptual insight model

No Adapt	Adapt
No-Adapt-See No-Adapt-Believe	Adapt-See Adapt-Believe
1 μ_A (fixed, shared) 2 σ 2 μ_L 2 $k_{\text{confidence}}$	1 μ_A (fixed, shared) 2 σ 2 μ_L 2 $k_{\text{confidence}}$

14 parameters to fit total

Maximum likelihood estimation (MLE)

Perceptual insight model

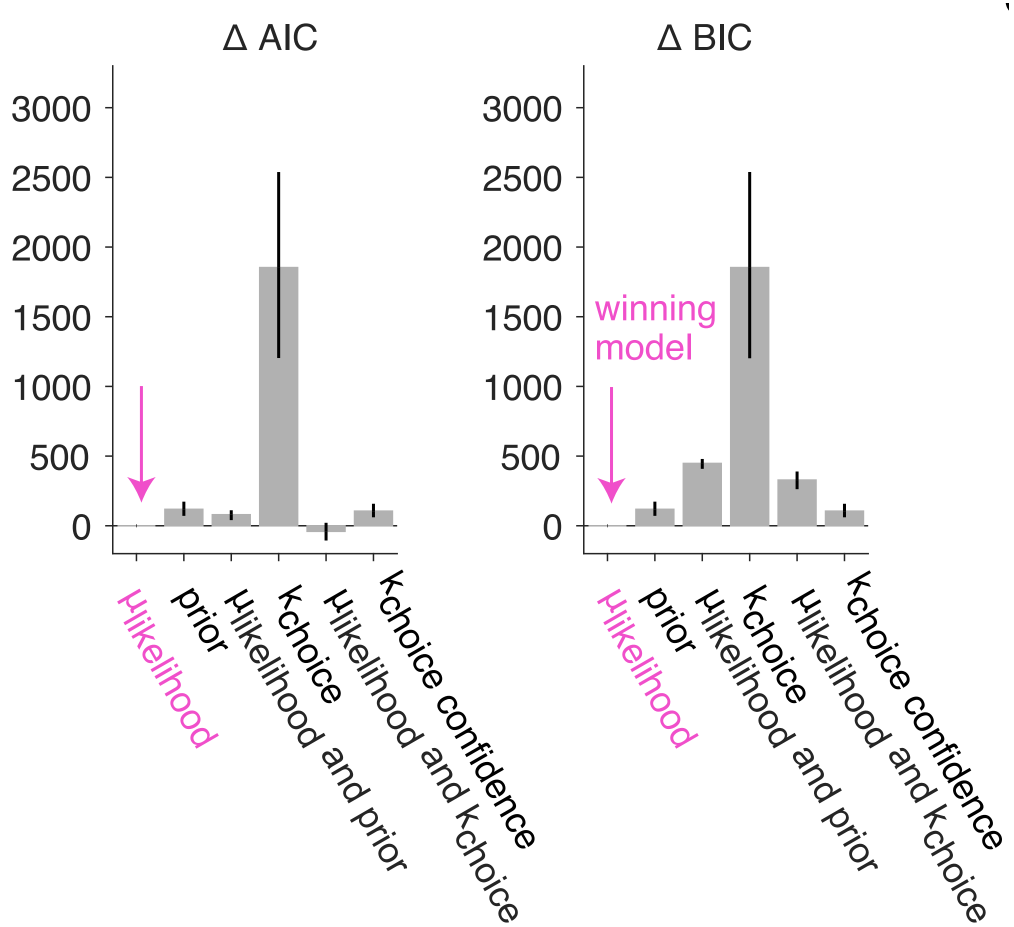
Response bias model

Stage	Model					
	Perceptual insight "$\mu_{\text{likelihood}}$"	**"prior"**	"$\mu_{\text{likelihood}}$ **+ prior**"	Late compensation "k_{choice}"	"$\mu_{\text{likelihood}} + k_{\text{choice}}$"	"$k_{\text{choice confidence}}$"
Early	$\mu_{\text{encoding}} \times 2$ (fixed) $\sigma_{\text{encoding}} \times 4$	$\mu_{\text{encoding}} \times 2$ (fixed) $\sigma_{\text{encoding}} \times 4$	$\mu_{\text{encoding}} \times 2$ (fixed) $\sigma_{\text{encoding}} \times 4$	$\mu_{\text{encoding}} \times 2$ (fixed) $\sigma_{\text{encoding}} \times 4$	$\mu_{\text{encoding}} \times 2$ (fixed) $\sigma_{\text{encoding}} \times 4$	$\mu_{\text{encoding}} \times 2$ (fixed) $\sigma_{\text{encoding}} \times 4$
Intermediate	$\mu_{\text{likelihood}} \times 4$	prior $\times$ 4	$\mu_{\text{likelihood}} \times 4$ prior $\times$ 4		$\mu_{\text{likelihood}} \times 4$	
Late	$k_{\text{confidence}} \times 4$	$k_{\text{confidence}} \times 4$	$k_{\text{confidence}} \times 4$	$k_{\text{confidence}} \times 4$ $k_{\text{choice}} \times 4$	$k_{\text{confidence}} \times 4$ $k_{\text{choice}} \times 4$	$k_{\text{confidence}} \times 4$ $k_{\text{choice}} \times 4$

$$\hat{C} = \begin{cases} 1, & \text{if } d > 0 \\ -1, & \text{otherwise} \end{cases}$$

$$\hat{C} = \begin{cases} 1, & \text{if } d > k_{\text{choice}} \\ -1, & \text{otherwise} \end{cases}$$

Model comparison: The best fitting model is the perceptual insight model



Parameter recovery

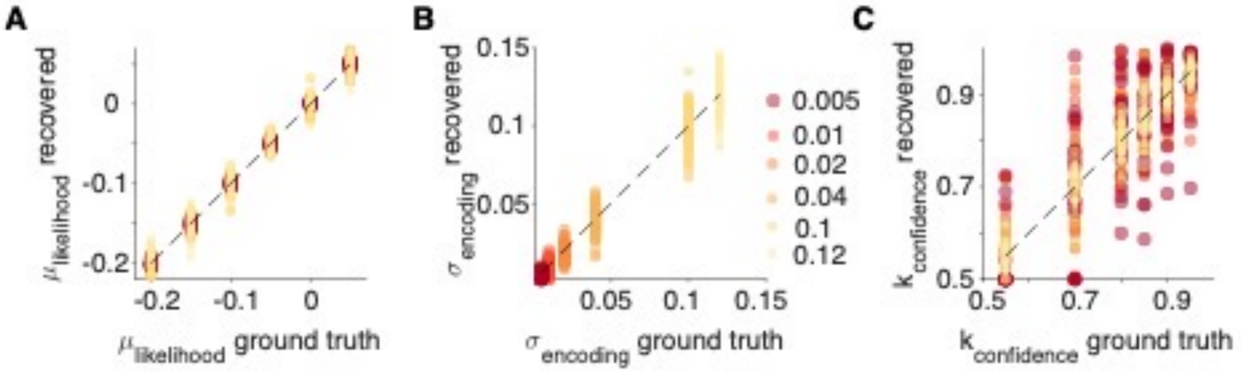
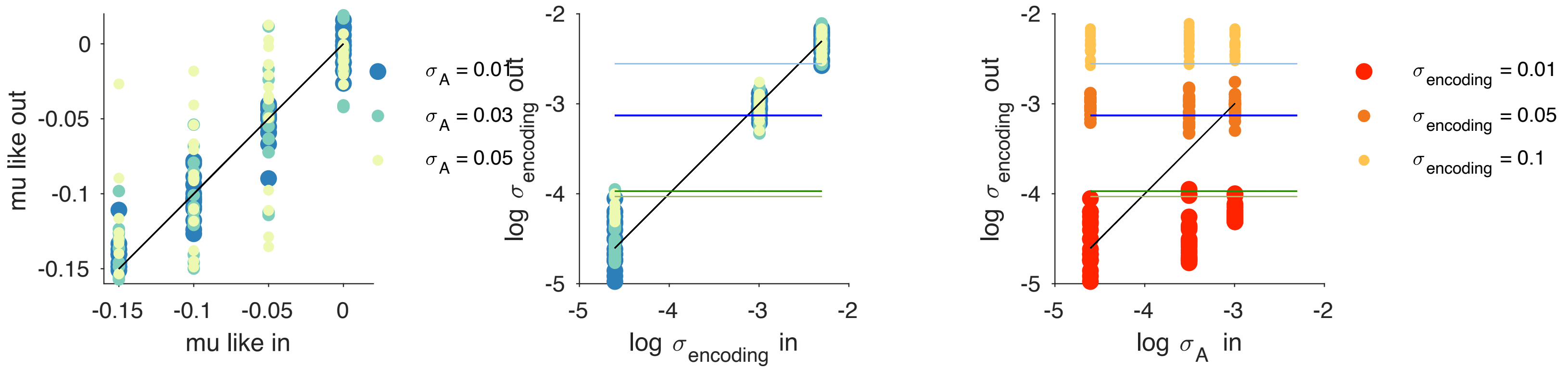


Figure S7: **Parameter recovery in the $\mu_{\text{likelihood}}$ model, based on simulated datasets with 121 trials each. A)** $\mu_{\text{likelihood}}$. **B)** σ_{encoding}. **C)** $k_{\text{confidence}}$. The Spearman correlations for parameter recovery were 0.98 for $\mu_{\text{likelihood}}$, 0.97 for σ_{encoding} and 0.85 for $k_{\text{confidence}}$.



Bayesian model and inference in this task

Sensory encoding

Category

$p(C=1) = p(C=-1) = \frac{1}{2}$

Right (CW) Left (CCW)

(fixed everywhere, except that it will be fitted in the prior version of model)

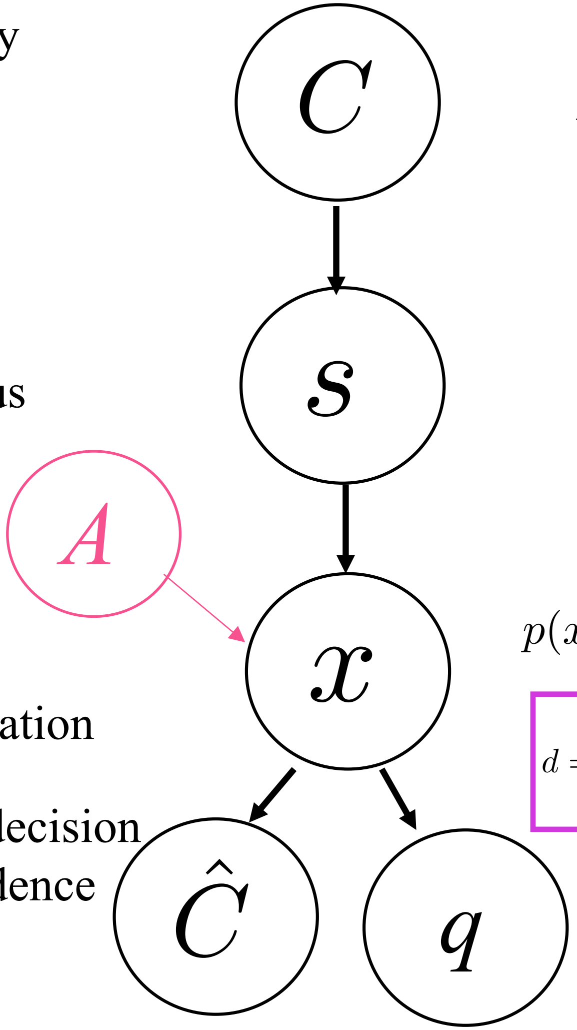
Stimulus

$p(s) = \mathcal{U}(s; -0.3, 0.3)$

Adaptor

Internal representation

$p(x|s) = \mathcal{N}(x; s - \mu_A, \sigma)$



$$\boxed{d = \log \frac{p(C=1|x)}{pC=-1|x)}}$$

d: decision variable

-|d|: perceptual-decision uncertainty

Decision/ Inference

Category decision and Confidence

$$p(C=1|x) = \frac{1}{1+e^{-d}}$$

$$\hat{C} = \underset{C}{\mathrm{argmax}}\, p(C|x)$$

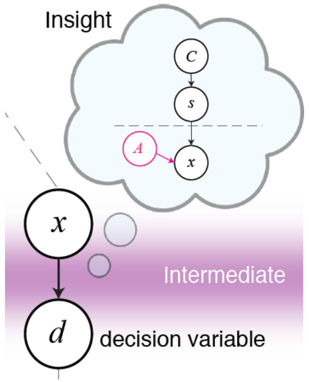
$$\text{confidence} = p(C=\hat{C}|x) = \frac{1}{1+e^{|d|}}$$

$$q = \begin{cases} 1, & \text{if confidence} > k_{\text{confidence}} \\ 0, & \text{otherwise} \end{cases}$$

Green and Swets, 1966
Knill and Pouget, 2004,
Kording and Wolpert, 2006,
Adler and Ma, 2018

Inference

$$\boxed{d = \log \frac{p(C=1|x)}{pC=-1|x)}}$$



Perceptual insight as incorporation of knowledge of the distortion -μ_L- into the decision variable

$$d = \log \frac{p(C=1)}{1-p(C=1)} + \log \left(\frac{\Phi(0.3-\mu_L-x;0,\sigma) - \Phi(-\mu_L-x;0,\sigma)}{\Phi(-\mu_L-x;0,\sigma) - \Phi(-0.3-\mu_L-x;0,\sigma)} \right)$$

Scaled with the sensory noise σ

Φ Cumulative density function (cdf) of the Gaussian