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Computational modeling of interoceptive dysfunction across psychiatric disorders

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How well do you understand the concept of interoception?

A. Not very well

B. A little

C. Moderately

D. Quite well

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No conflicts of interest to disclose

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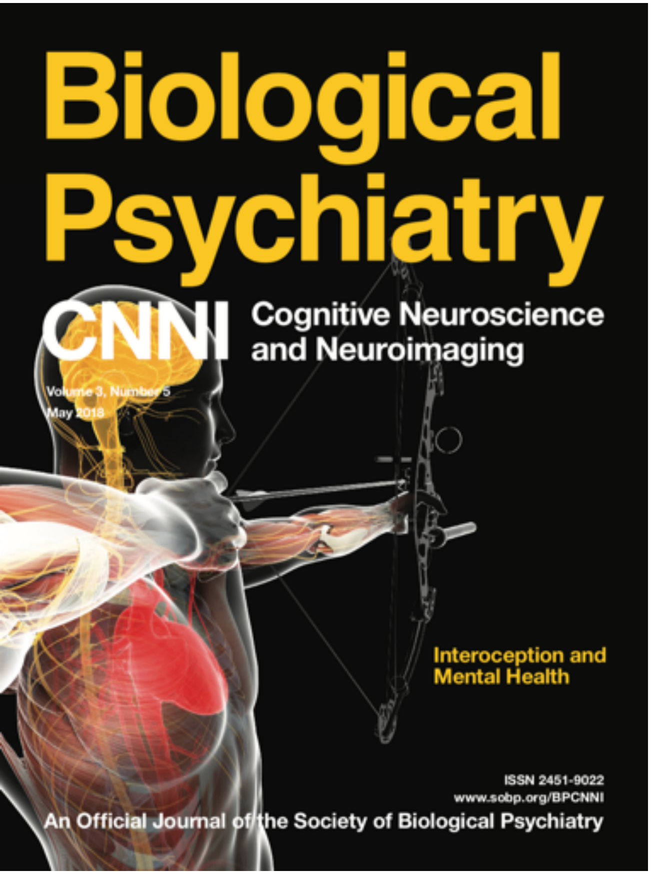
The Laureate Institute for Brain Research (LIBR) is a nonprofit clinical neuroscience research institute focused on discovering novel therapies and tools for helping individuals with mental illness.

Review

Interoception and Mental Health: A Roadmap

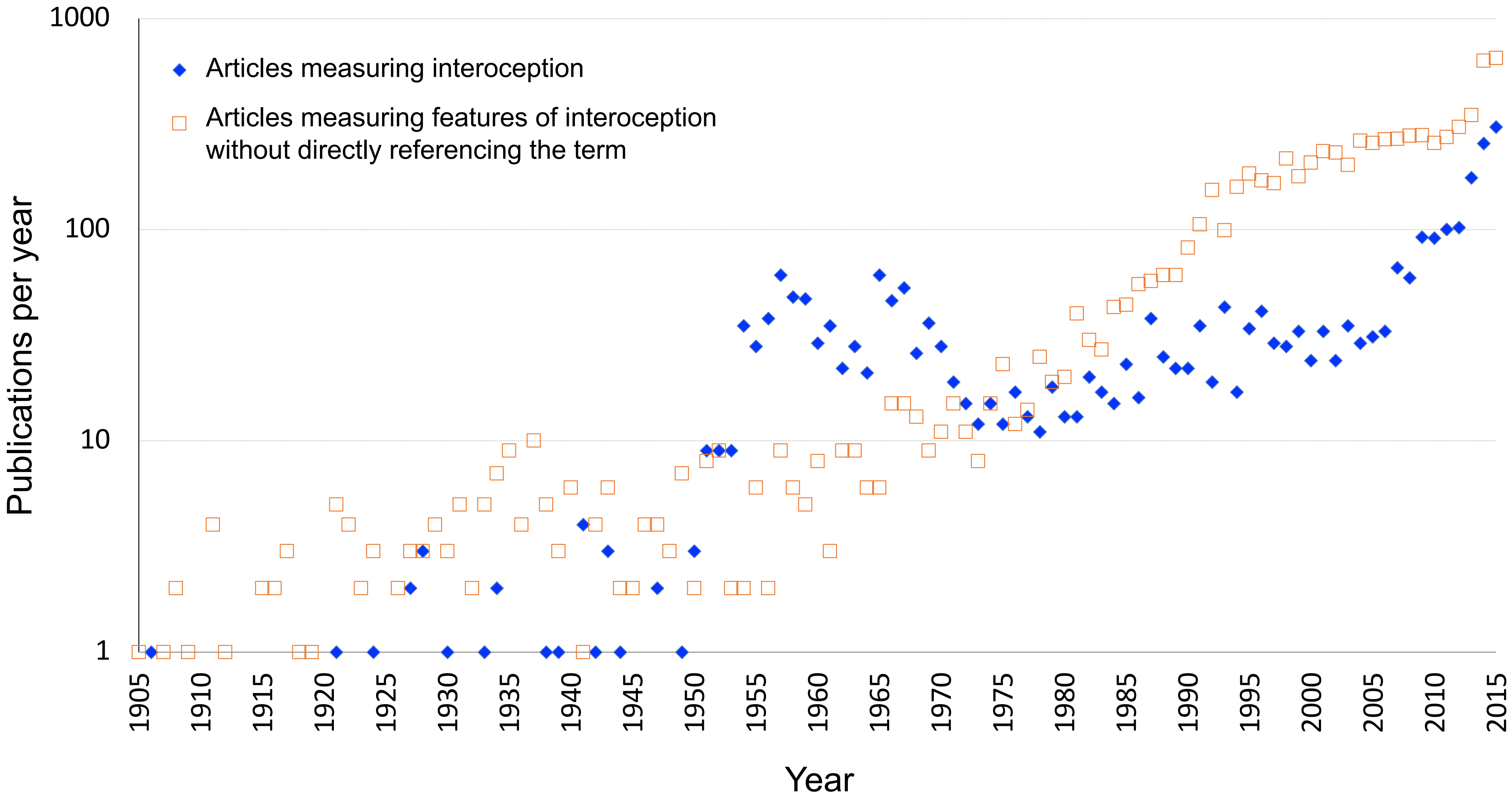
Sahib S. Khalsa, Ralph Adolphs, Oliver G. Cameron, Hugo D. Critchley, Paul W. Davenport, Justin S. Feinstein, Jamie D. Feusner, Sarah N. Garfinkel, Richard D. Lane, Wolf E. Mehling, Alicia E. Meuret, Charles B. Nemeroff, Stephen Oppenheimer, Frederike H. Petzschner, Olga Pollatos, Jamie L. Rhudy, Lawrence P. Schramm, W. Kyle Simmons, Murray B. Stein, Klaas E. Stephan, Omer Van den Bergh, Ilse Van Diest, Andreas von Leupoldt, Martin P. Paulus, and the Interoception Summit 2016 participants



Khalsa et al. (2018)
Biological Psychiatry CNNI

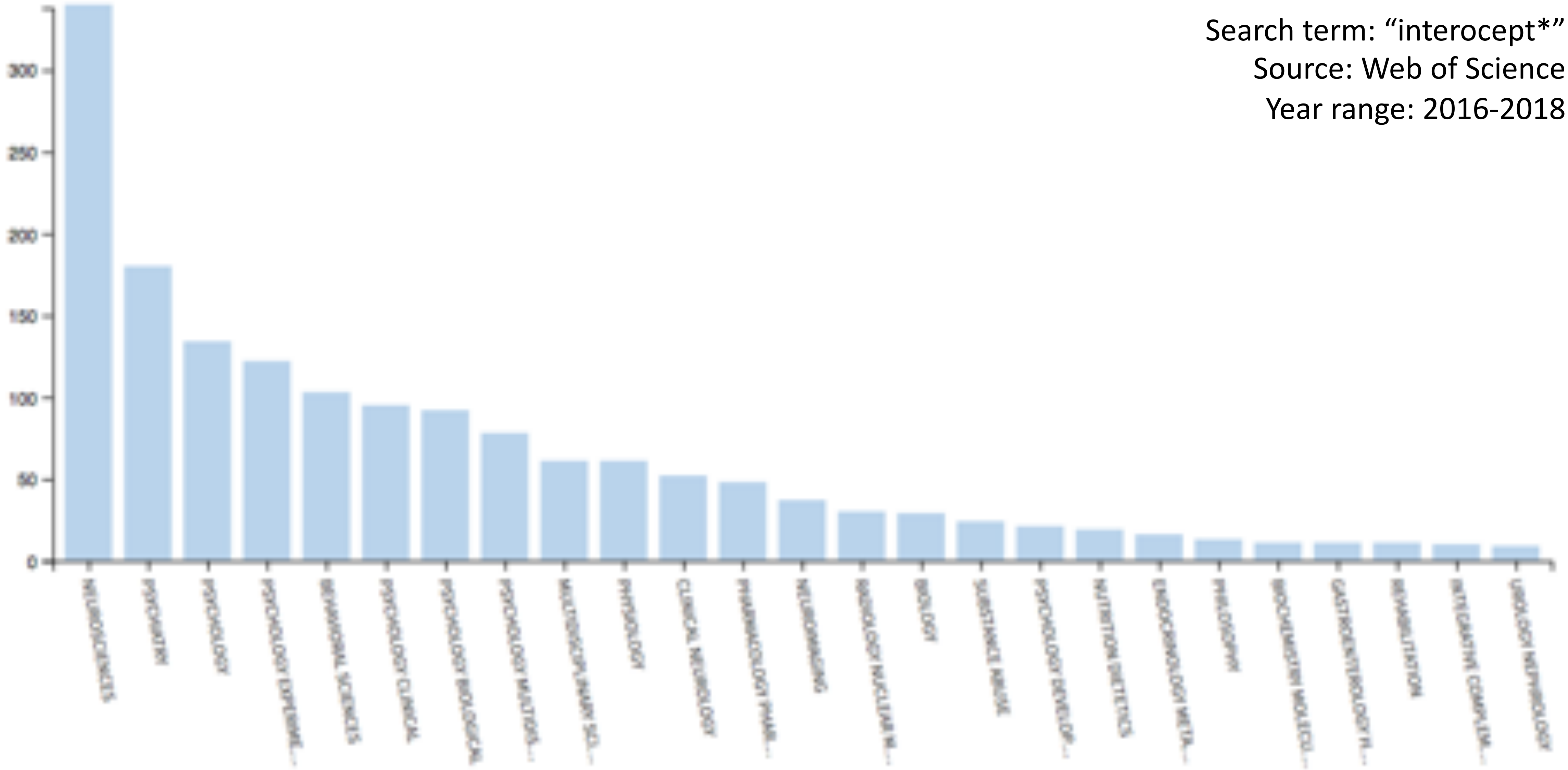
Interoception refers to the process by which the nervous system senses, interprets, and integrates signals originating from within the body, providing a moment-by-moment mapping of the body's internal landscape across conscious and unconscious levels.

It forms the basis for regulation of internal body signals, participating in a '**brain-body feedback loop**'



Khalsa et al., (2018), *Biological Psychiatry CNNI*

Search term: “interocept*”
Source: Web of Science
Year range: 2016-2018

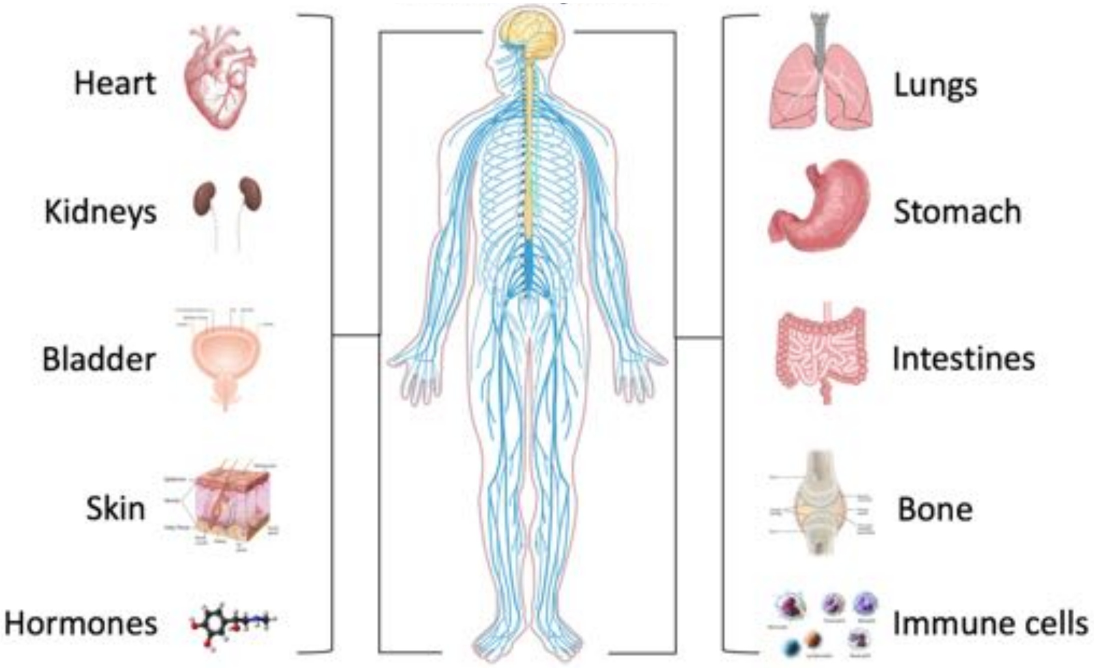


Interoception is critical for ensuring homeostasis

Table 1. Physiological Processes Often Ascribed to Interoception

Nonpainful
Cardiovascular, respiratory, gastrointestinal (esophageal, gastric, intestinal, colorectal), bladder, hunger, thirst, blood/serum (pH, osmolality, glucose), temperature, vasomotor flush, air hunger, muscle tension, shudder, itch, tickle, genital sensation, sensual touch, fatigue
Painful
Visceral: kidney stone, pleuritic, angina, pericardial, bowel ischemia, pelvic, sickle crisis
Somatic: abscess/boil, bruising, myalgia, inflammation (systemic/laceration), headache
Skeletal: fractured/bruised bone, stress fracture, inflammatory/mechanical joint pain

Khalsa et al., (2018), *Biological Psychiatry CNNI*



https://en.wikipedia.org/wiki/Interoception


Cardiovascular
Hunger
Palpitation
Gastrointestinal
(esophageal,
gastric, intestinal, colorectal)
Respiratory
Angina
pH
Itch
Vasomotor flush
Dyspnea
Urinary
Thirst
Kidney pain
Fatigue
Temperature
Pleasurable touch
Glucose

Interoceptive dysfunction in psychiatric disorders

Psychiatric Disorder	Symptoms	Signs	Sample Studies
Panic Disorder	Palpitations, chest pain, dyspnea, choking, nausea, dizziness, flushing, depersonalization/derealization	Elevated heart rate and/or blood pressure, exaggerated escape, startle, and flinching	(5,140,141)
Depression	Increased or decreased appetite, fatigue, lethargy	Weight gain, weight loss, psychomotor slowing	(142,143)
Eating Disorders	Hunger insensitivity, food anxiety, gastrointestinal complaints	Severe food restriction, severe weight loss, binging, purging, compulsive exercise	(72,98)
Somatic Symptom Disorders	Multiple current physical and nociceptive symptoms	Medical observations do not correspond with symptom report	(144,145)
Substance Use Disorders	Physical symptoms associated with craving, intoxication, and/or withdrawal (drug specific)	Elevated/decreased: heart rate, respiratory rate, and/or blood pressure, pupil dilation/constriction, others (drug specific)	(101,146,147)
Posttraumatic Stress Disorder	Autonomic hypervigilance, depersonalization/derealization	Exaggerated startle, flinching, and/or escape responses, elevated heart rate and/or blood pressure	(148)
Generalized Anxiety Disorder	Muscle tension, headaches, fatigue, gastrointestinal complaints, pain	Trembling, twitching, shaking, sweating, nausea, exaggerated startle	(149,150)
Depersonalization/Derealization Disorder	Detachment from one's body, head fullness, tingling, lightheadedness	Physiological hyporeactivity to emotional stimuli	(151,152)
Autism Spectrum Disorders	Skin hypersensitivity	Selective clothing preferences	(107,153,154)

Khalsa et al., (2018), *Biological Psychiatry CNNI*

Interoceptive dysfunction in psychiatric disorders

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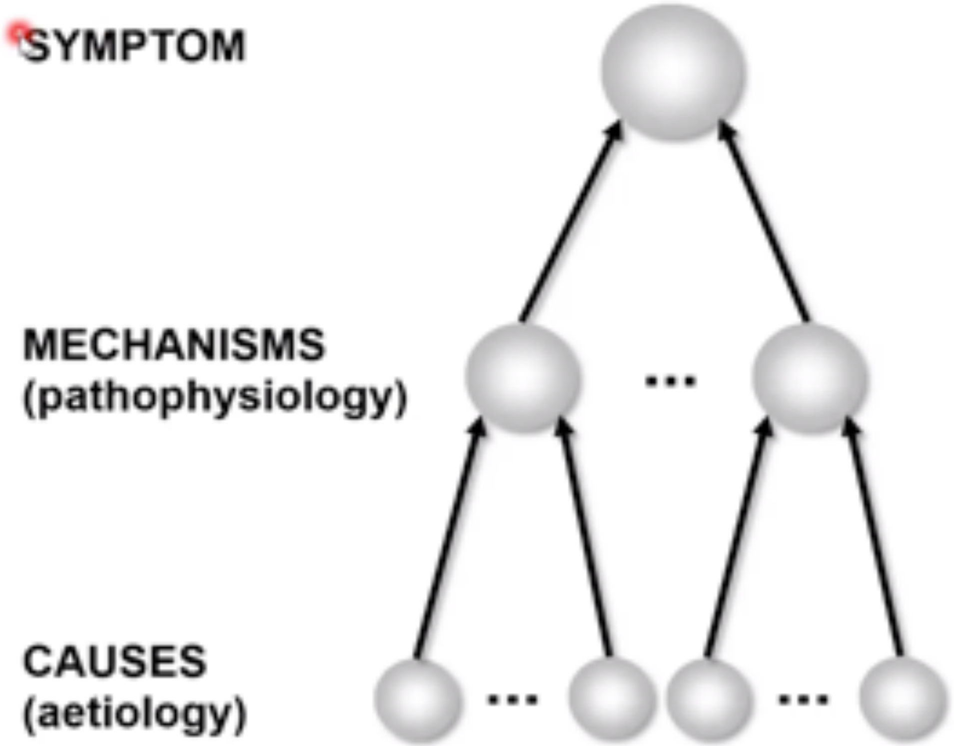


Stephan: *Translational Neuromodeling & Computational Psychiatry, in prep.*

Khalsa et al., (2018), *Biological Psychiatry CNNI*

Can **you** feel your heartbeat right now (without taking your pulse)?

A. Yes

B. No

How well can **you** feel your heartbeat?

40%
Ferguson & Katkin 1996

30%
Schneider et al 1998

17%
Wiens et al 2000

25%
Mesas & Chica 2003

34%
Average

47%
Mesas & Chica 2003

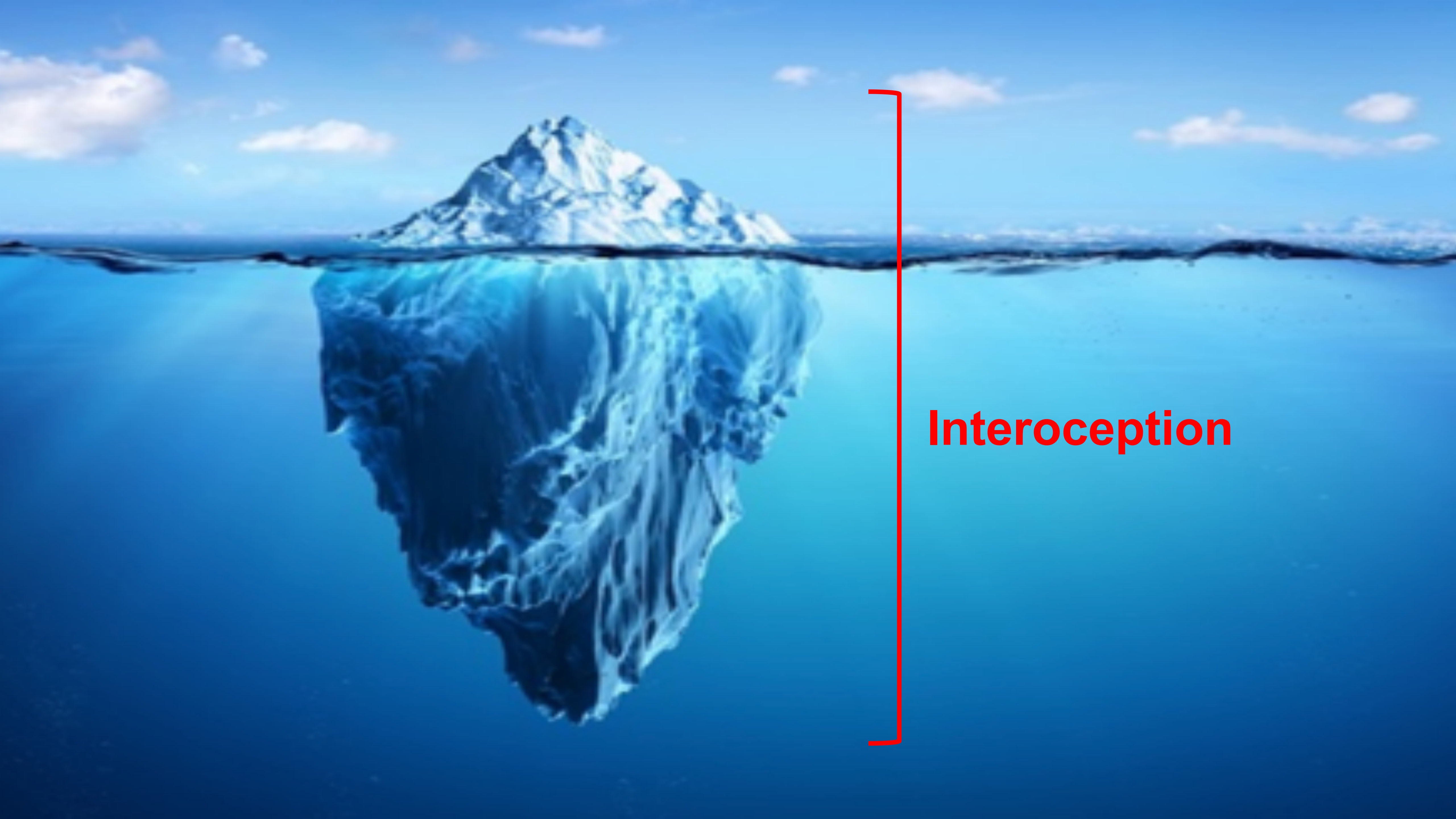
39%
Khalsa et al 2009
Meditation

33%
Katkin et al 2001

44%
Khalsa et al 2009
Meditation

35%
Heart transplant
Barsky et al 1998

See Khalsa & Lapidus (2016) *Front Psychiatry* for a review

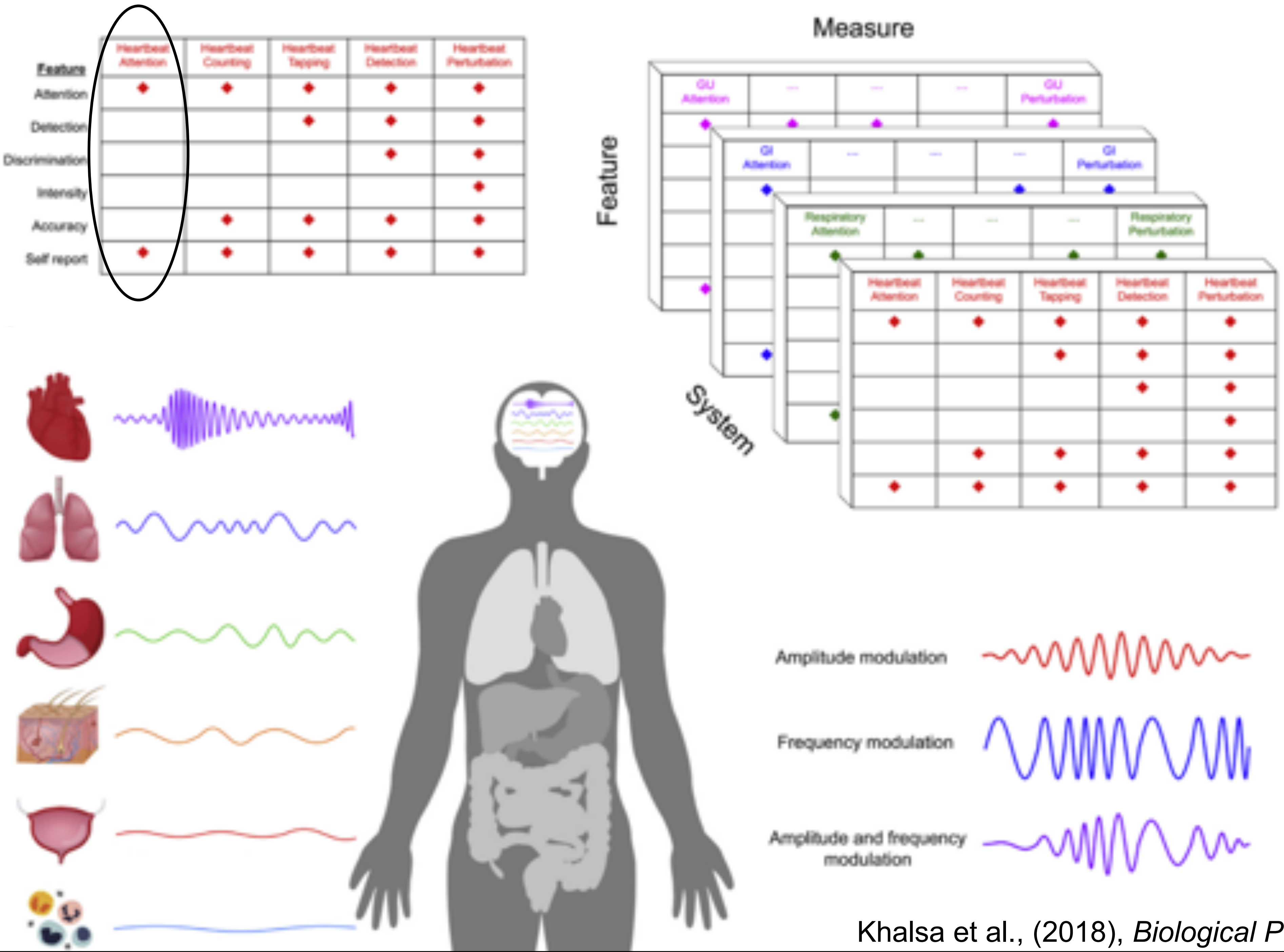

Interoception

Interoceptive awareness

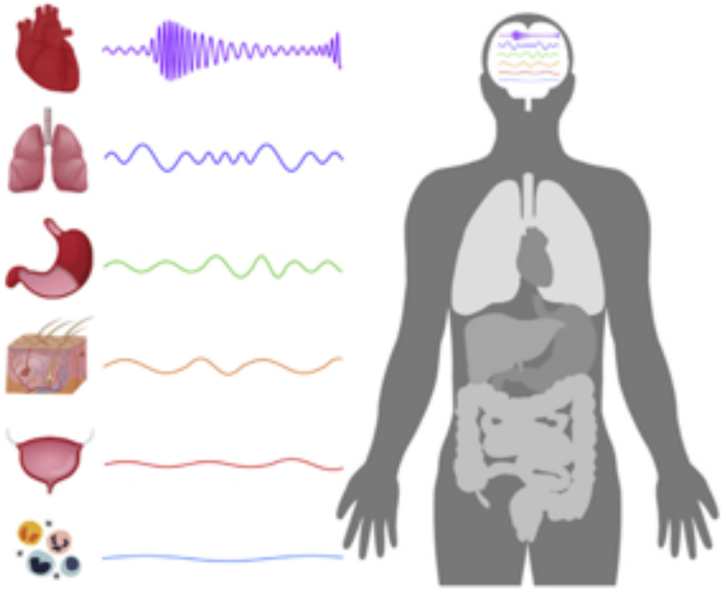
Table 2. Features of Interoceptive Awareness

Feature	Definition
Attention	Observing internal body sensations
Detection	Presence or absence of conscious report
Magnitude	Perceived intensity
Discrimination	Localize sensation to a specific channel or organ system and differentiate it from other sensations
Accuracy (Sensitivity)	Correct and precise monitoring
Insight	Metacognitive evaluation of experience/ performance (e.g., confidence–accuracy correspondence)
Sensibility	Self-perceived tendency to focus on interoceptive stimuli (trait measure)
Self-report Scales	Psychometric assessment via questionnaire (state/trait measure)

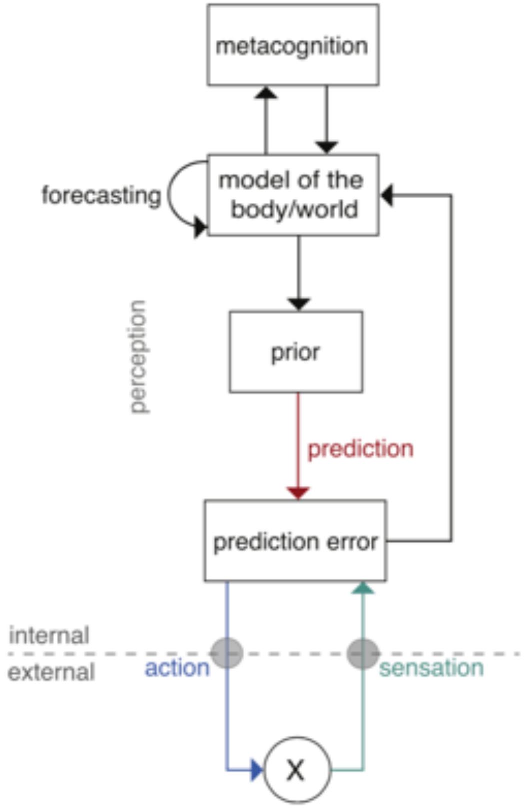
Khalsa et al., (2018), *Biological Psychiatry CNNI*

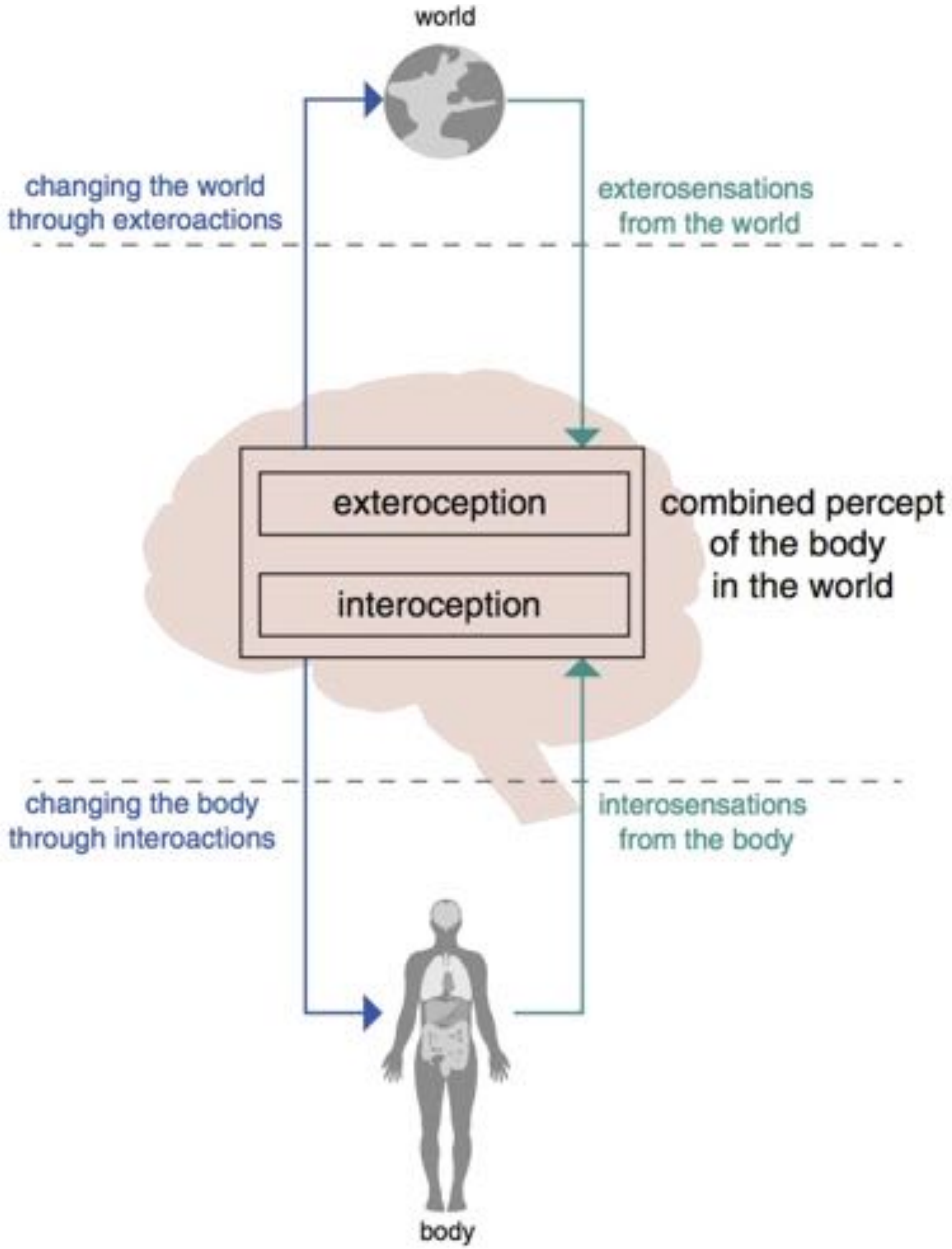


Khalsa et al., (2018), *Biological Psychiatry CNNI*



Khalsa et al., (2018)
Biological Psychiatry CNNI

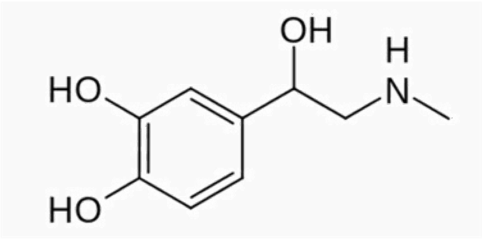




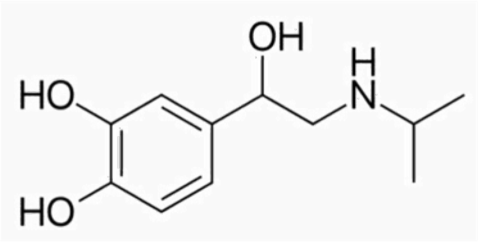
Petzschner et al (2017) *Biological Psychiatry*

One approach to studying signaling pathways involved in interoception

Approach: examine the brain's response to peripheral stress

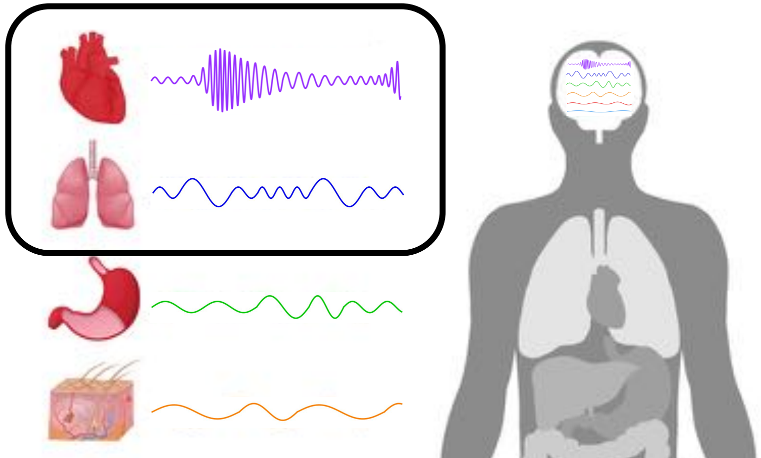


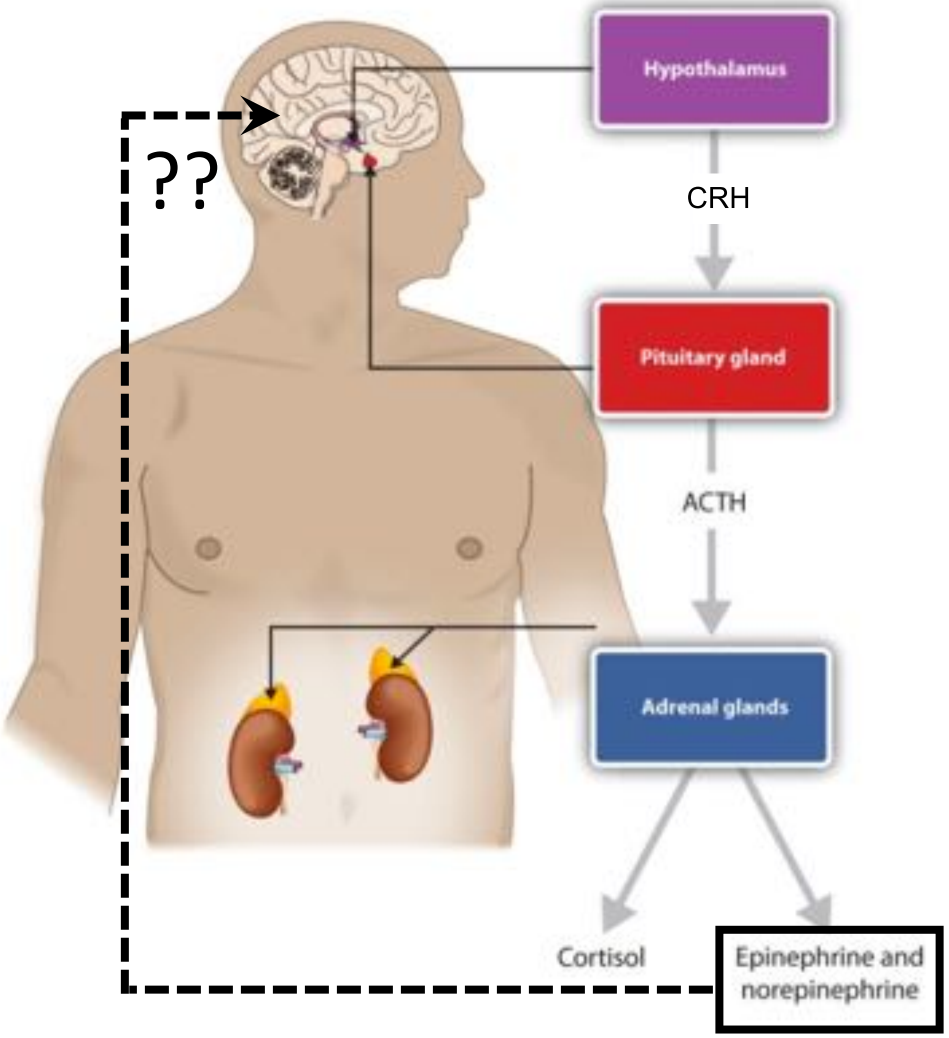
Epinephrine
(Adrenaline)



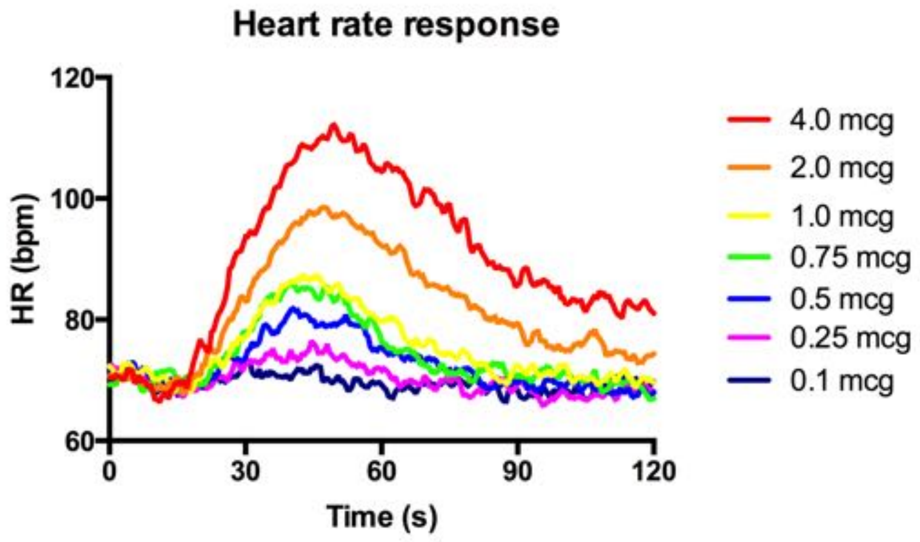
Isoproterenol

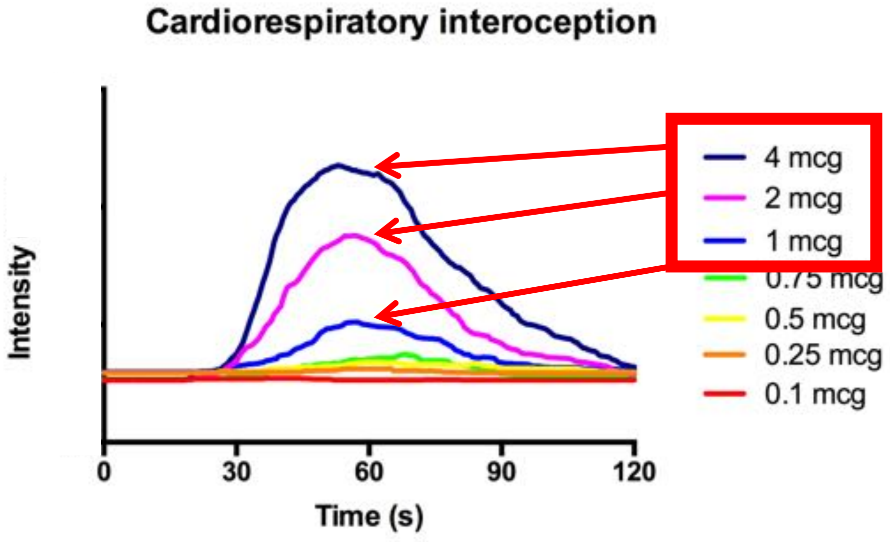
Isoproterenol stimulates beta-adrenergic receptors in the heart and lungs

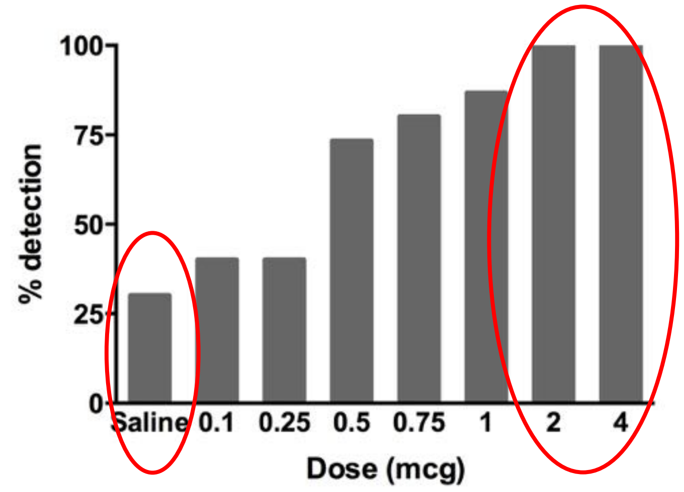


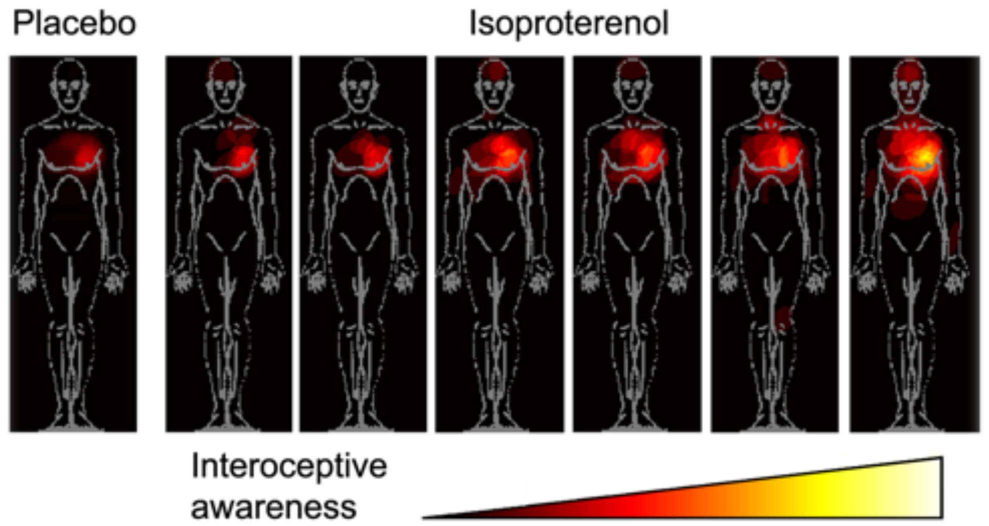


Isoproterenol increases sympathetic arousal and the conscious experience of cardiorespiratory sensations









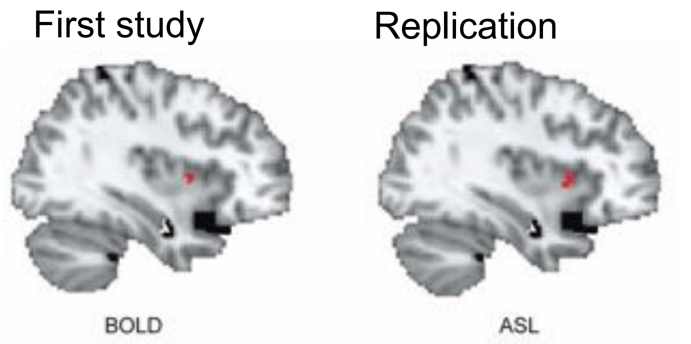
Khalsa et al. (2009) *Int. J. Psychophysiology*; Khalsa et al., (2016) *J. of Neuroscience*

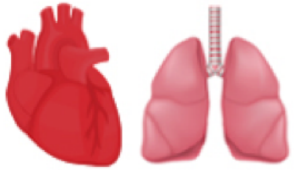
The Insular Cortex Dynamically Maps Changes in Cardiorespiratory Interoception

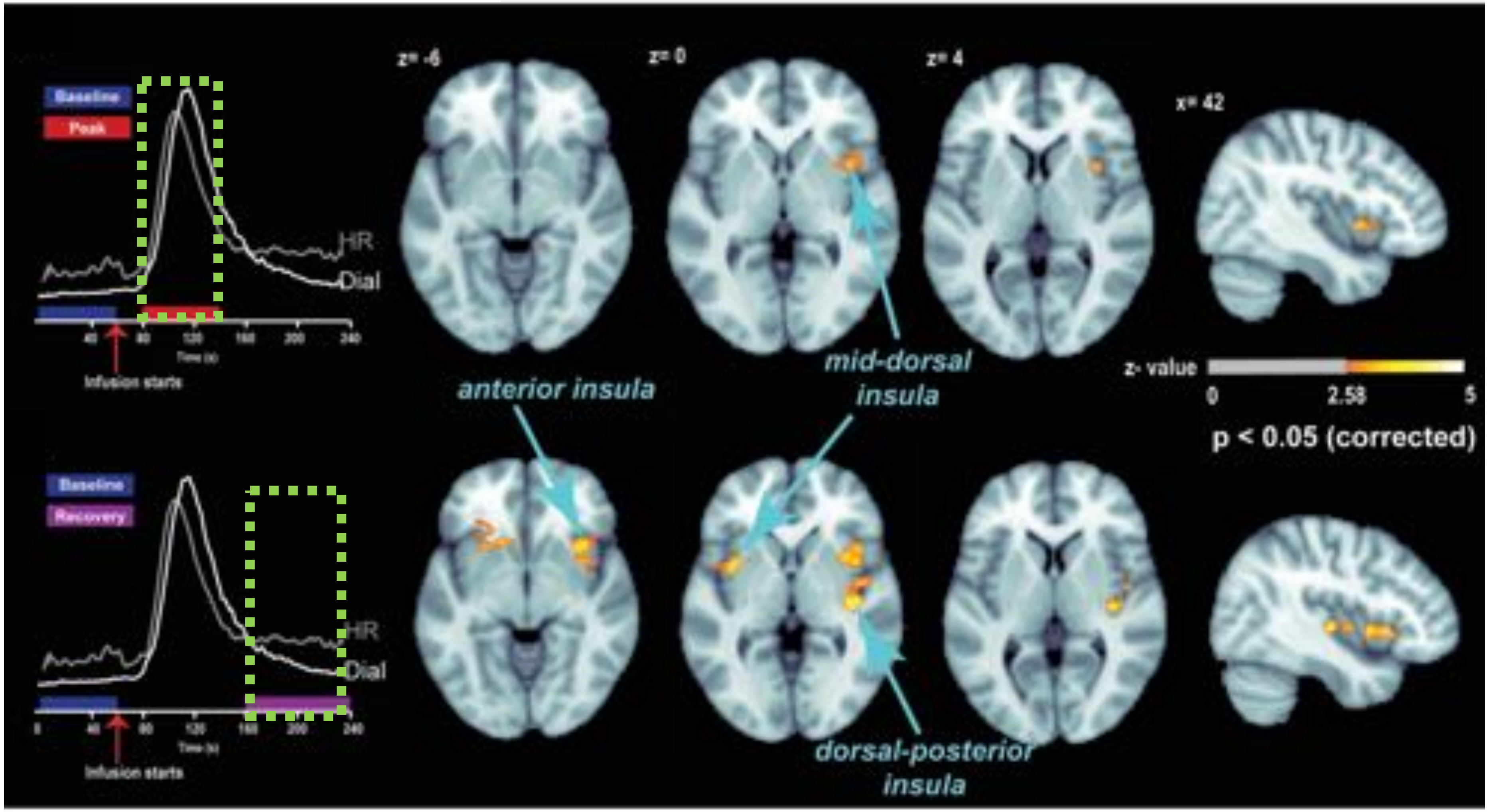
Neuropsychopharmacology (2018) 43, 426–434

Mahlega S Hassanpour[1], W Kyle Simmons[1,2], Justin S Feinstein[1,2], Qingfei Luo[1], Rachel C Lapidus[3], Jerzy Bodurka[1,4], Martin P Paulus[1] and Sahib S Khalsa*[1,2]

[1]Laureate Institute for Brain Research, Tulsa, OK, USA; [2]Oxley College of Health Sciences, University of Tulsa, Tulsa, OK, USA; [3]Department of Psychology, University of Tulsa, Tulsa, OK, USA; [4]Stephenson School of Biomedical Engineering, University of Oklahoma, Norman, OK, USA





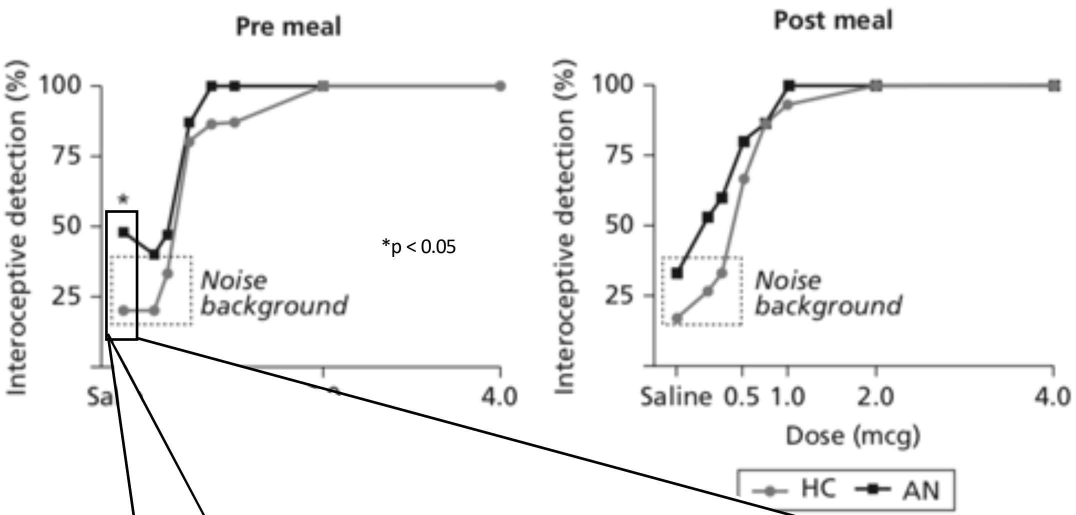


Erroneous interoceptive mapping in anorexia nervosa (AN)

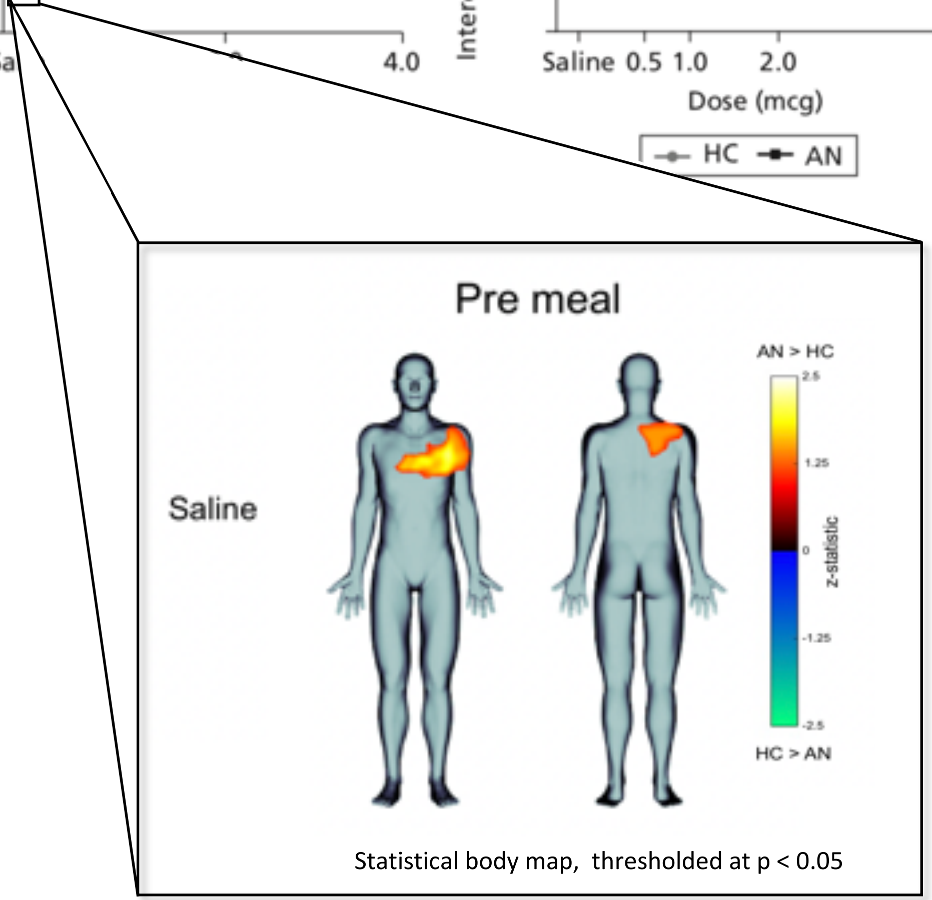
Individuals with AN reported greater false perceptions of the cardiorespiratory sensations during the pre meal time period

The false perceptions were associated with a greater localization of heartbeat sensations to the chest – in the absence of any stimulation!

These "*visceral illusions*" suggest that AN is associated with an abnormal representation of the heartbeat, particularly before anxiety-provoking meals



Khalsa et al. (2015)
Int. J. Eating Disorders



Statistical body map, thresholded at $p < 0.05$

Khalsa et al. (2018)
Front Psychiatry

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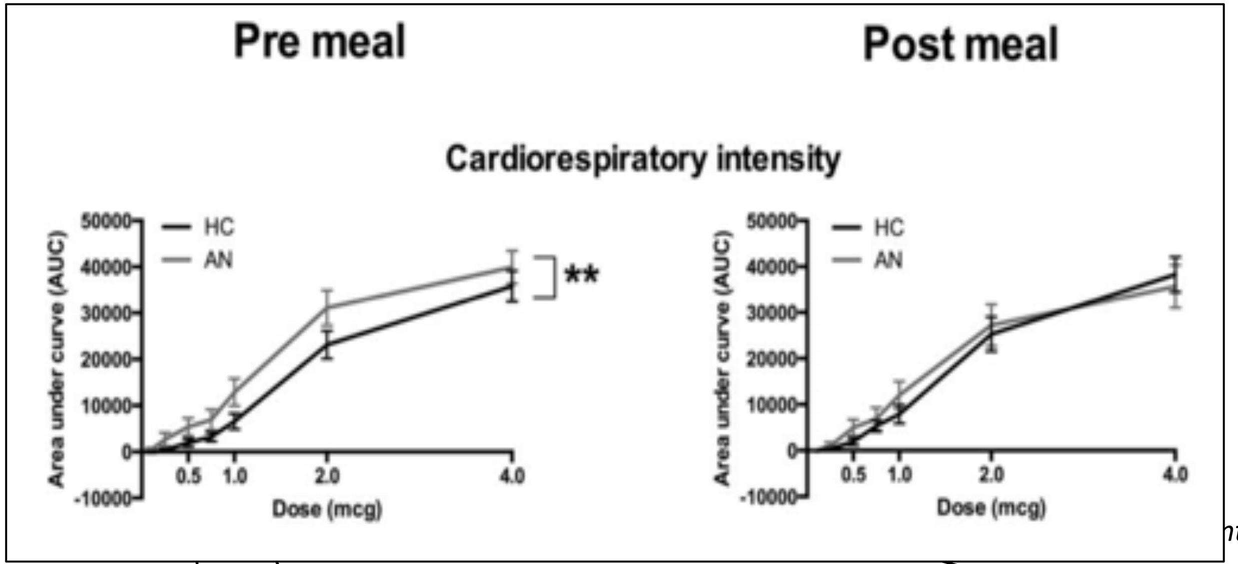

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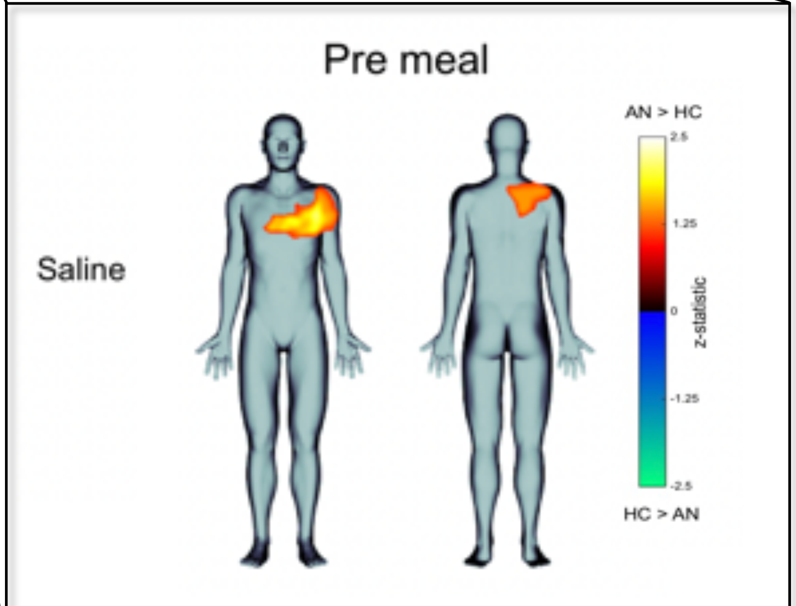

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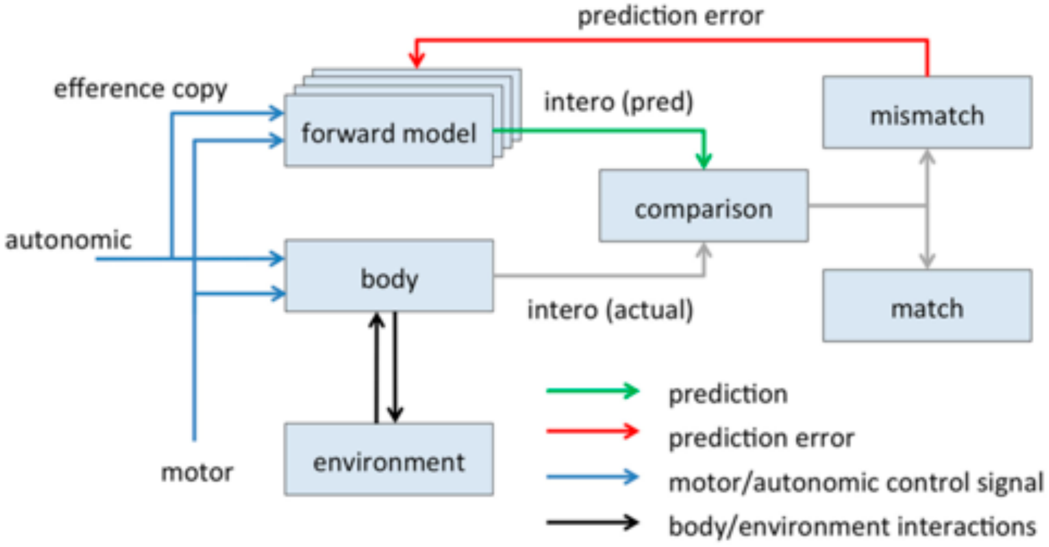
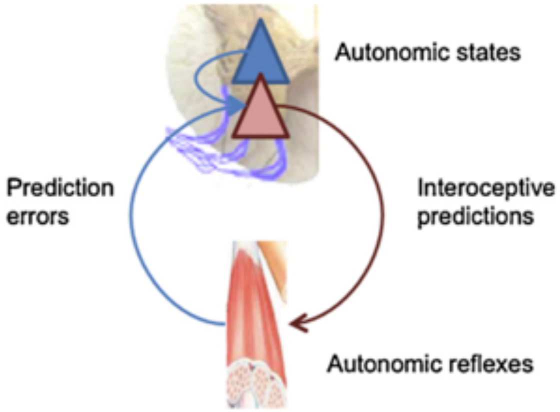
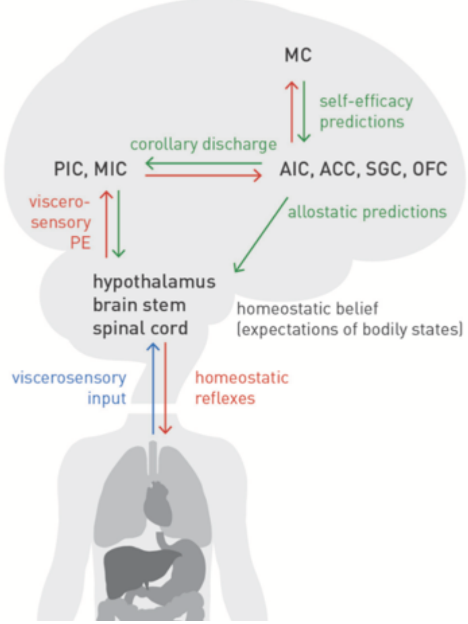


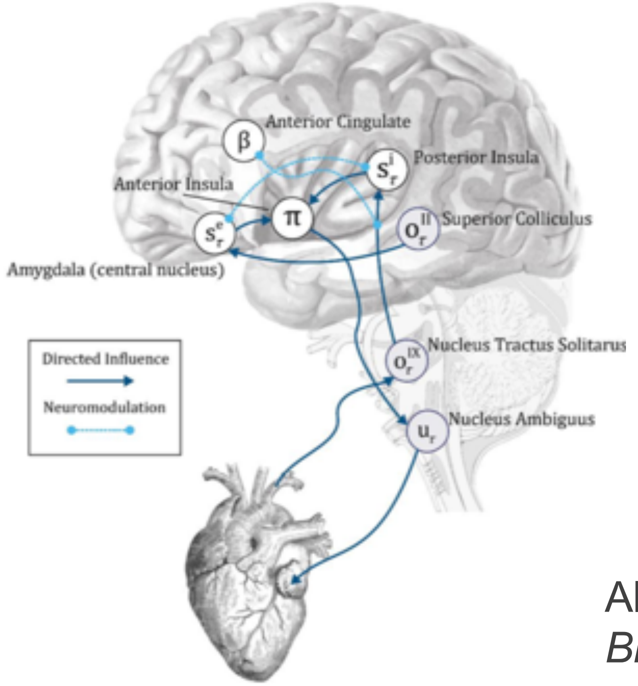
Seth, Suzuki & Critchley (2011), *Front Psychology*

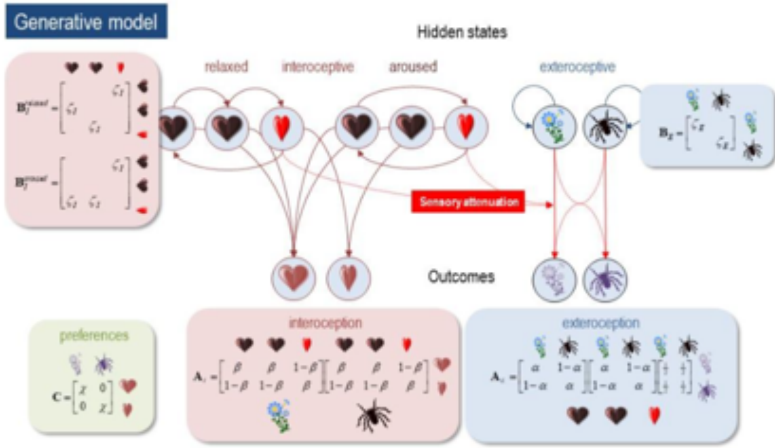


Pezzulo, Rigoli & Friston (2015), *Prog Neurobio*

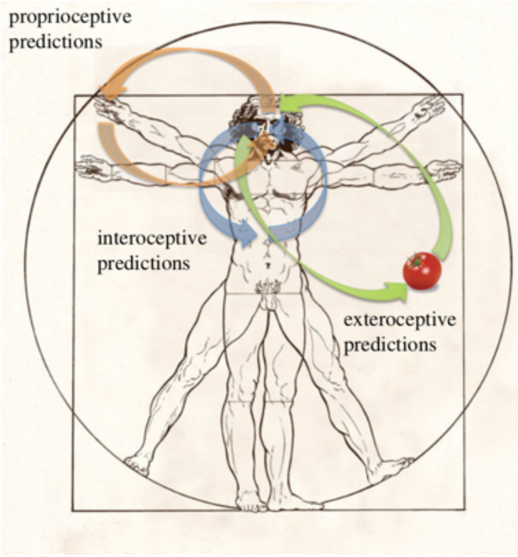


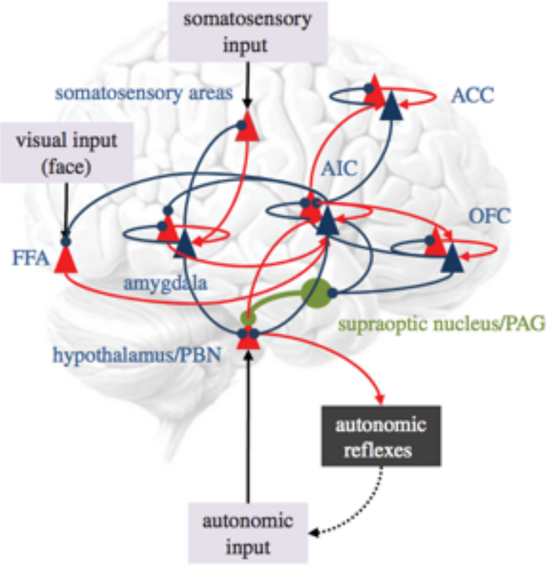
Stephan et al. (2016), *Front Hum Nsci*



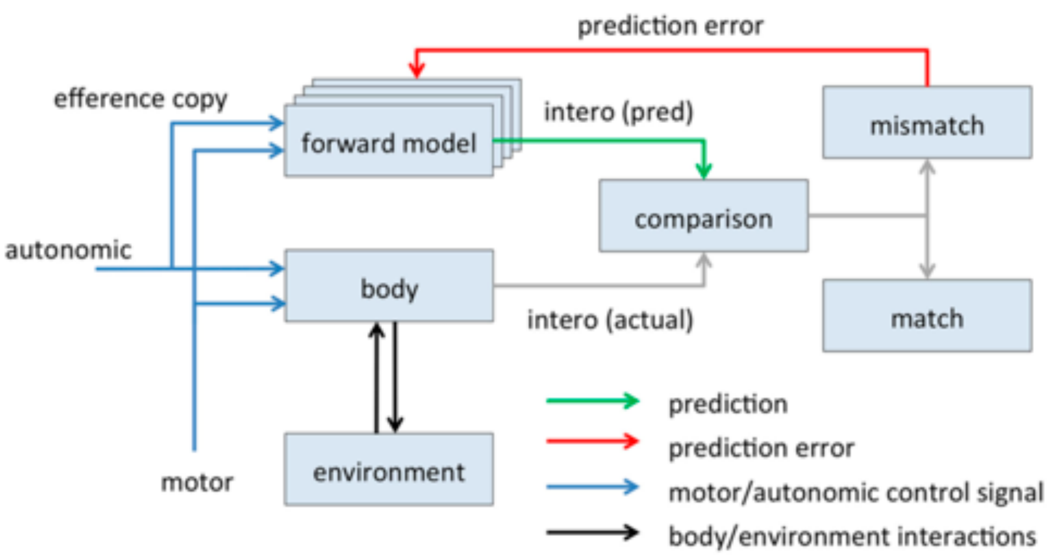


Allen, Levy, Parr, Friston (2019) *BioRxiv*





Seth & Friston (2016) *Phil Trans R Soc B*



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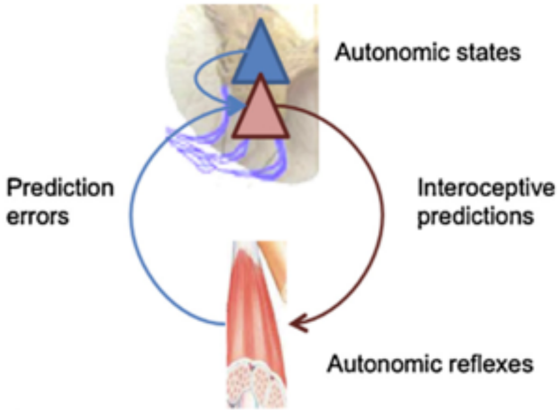

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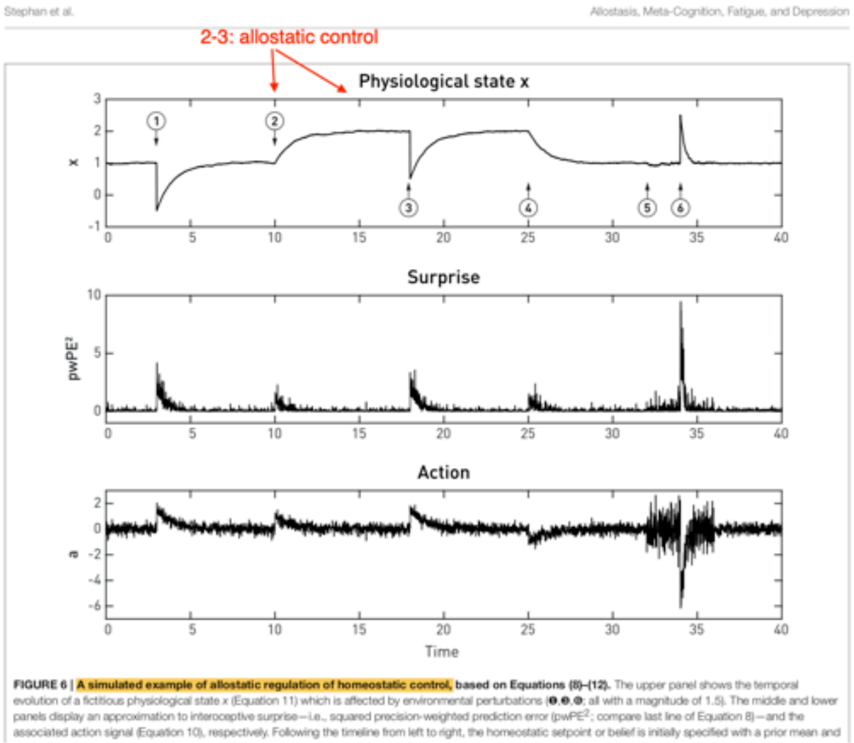

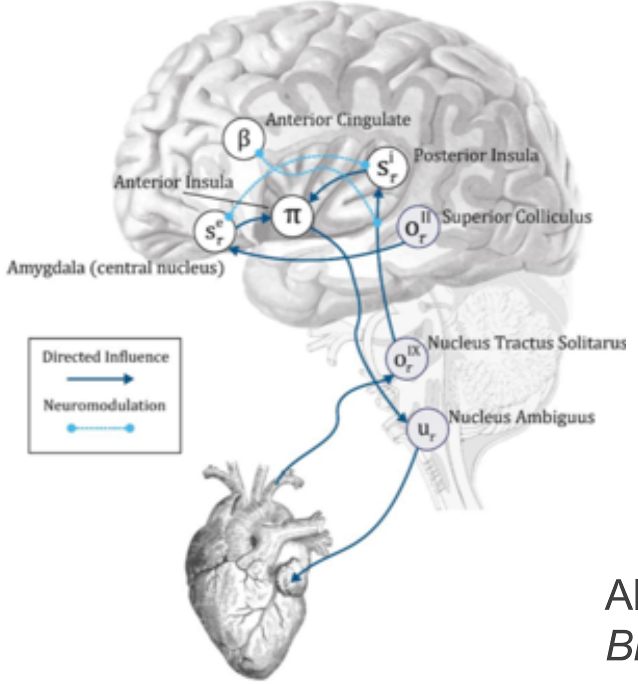

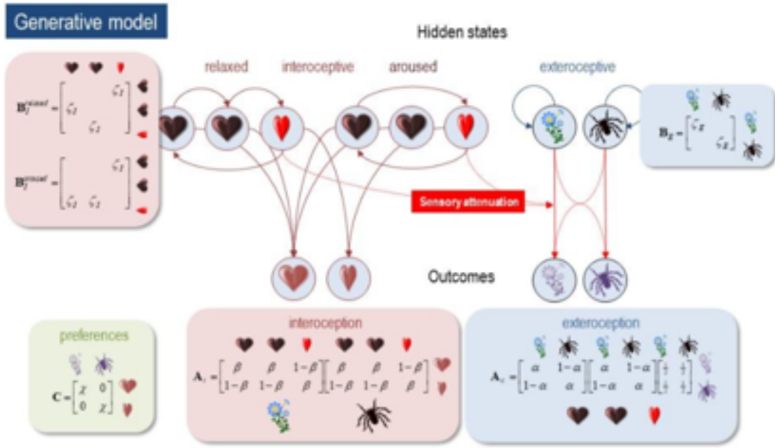

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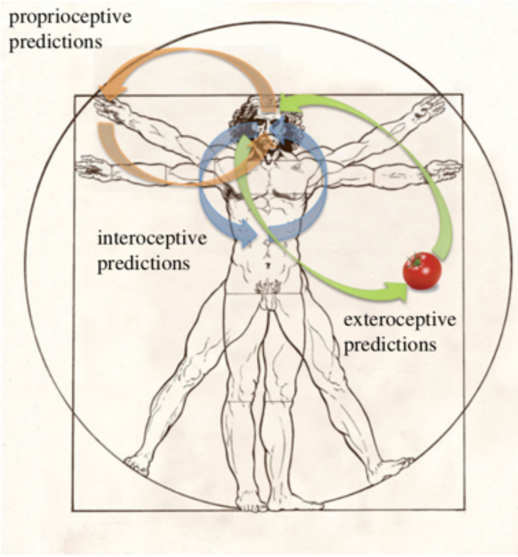
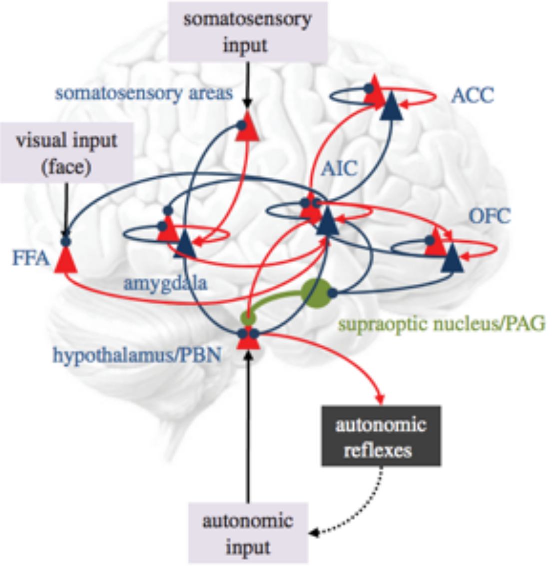


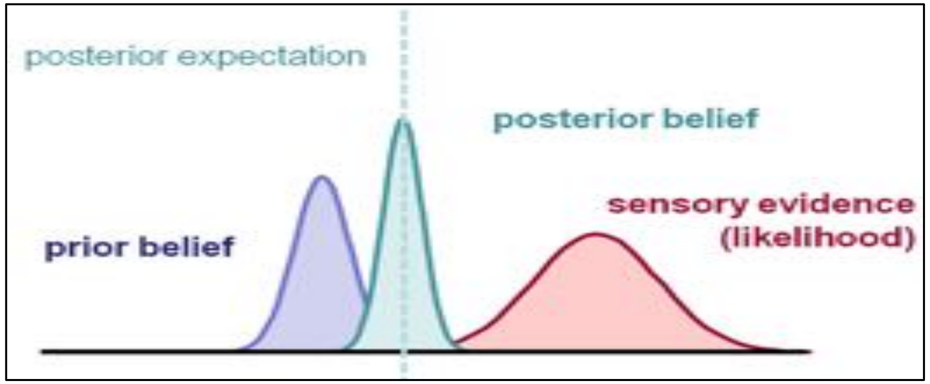


Seth & Friston (2016) *Phil Trans R Soc B*

Computational dysfunction

- Main idea - an **inability** of the brain to **update its model of the body** in the face of interoceptive prediction errors

- Dysfunctional **precision-weighting**
  - Poor control of the relative influence of prior expectations and afferent bodily signals in perception



- In other words, the brain may **treat afferent bodily signals as though they are not reliable** indicators of bodily states
  - leading perception to be insufficiently constrained by true visceral states
  - Perception is then primarily determined by (in many cases inaccurate/maladaptive) prior expectations.

- However, it's unclear whether **prior expectations** are **over-weighted** or **afferent signals** are **under-weighted**
  - Role of attention-mediated **learning** is also unclear

Annual Review of Clinical Psychology (2019)

An Active Inference Approach to Interoceptive Psychopathology

Martin P. Paulus,[1] Justin S. Feinstein,[1,2] and Sahib S. Khalsa[1,2]

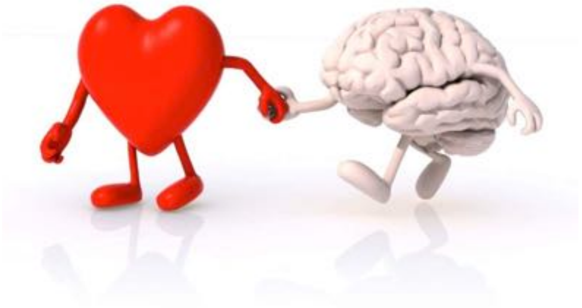
Abstract

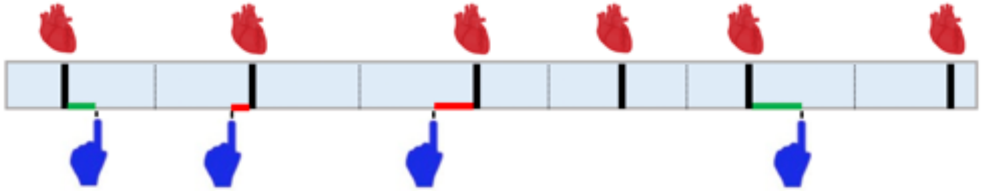
Interoception refers to the process by which the nervous system senses and integrates signals originating from within the body, providing a momentary mapping of the body's internal landscape and its relationship to the outside world. Active inference is based on the premise that afferent sensory input to the brain is constantly shaped and modified by prior expectations. In this review we propose that interoceptive psychopathology results from two primary interoceptive dysfunctions: First, individuals have abnormally strong expectations of the situations that elicit bodily change (i.e., hyperprecise priors), and second, they have great difficulty adjusting these expectations when the environment changes (i.e., context rigidity). Here we discuss how these dysfunctions potentially manifest in mental illness and how interventions aimed at altering interoceptive processing can help the brain create a more realistic model of its internal state.

Laureate Institute for Brain Research

A computational Bayesian model reveals a failure to adapt interoceptive precision estimates across depression, anxiety, eating, and substance use disorders

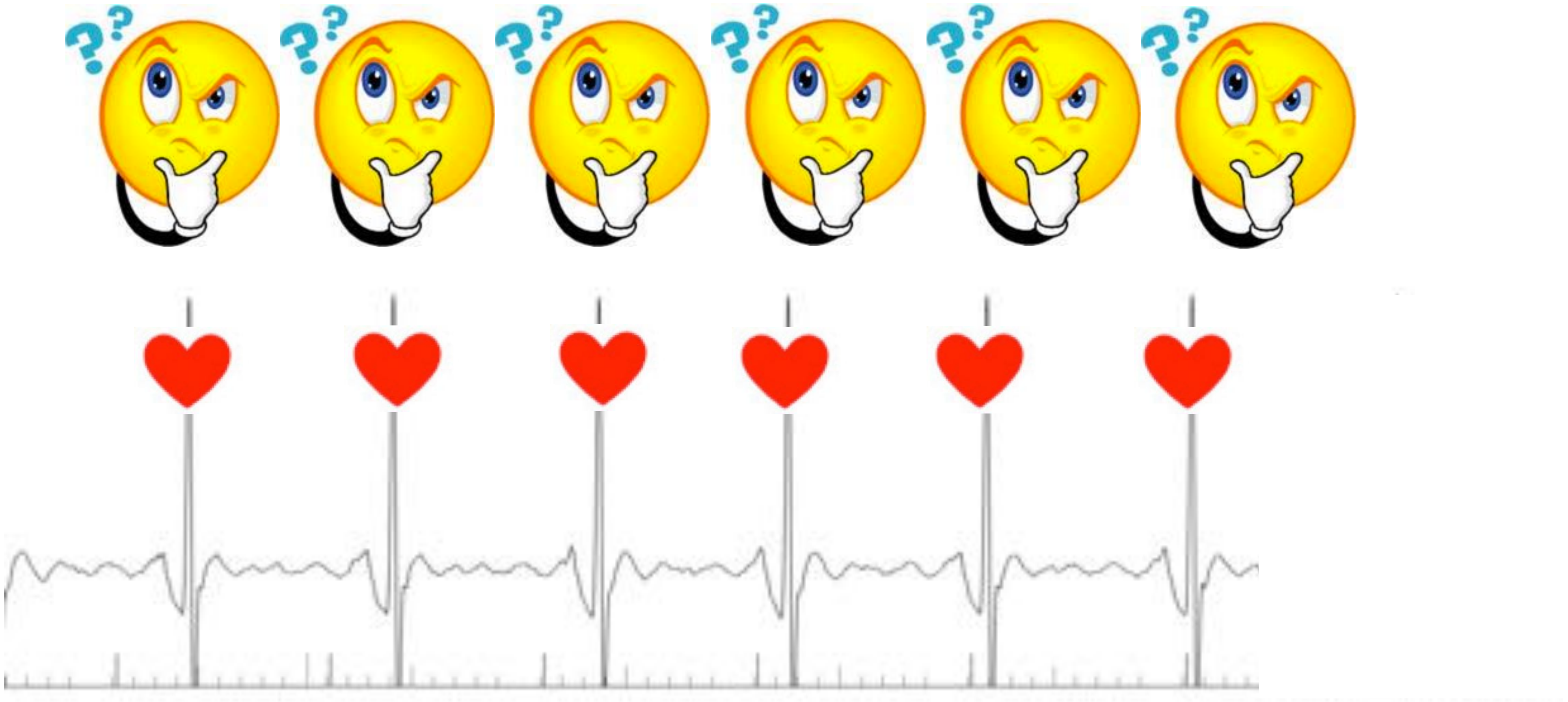
Ryan Smith, Rayus Kuplicki, Justin Feinstein, Katherine Forthman, Martin P. Paulus, Tulsa 1000 investigators, and Sahib S. Khalsa





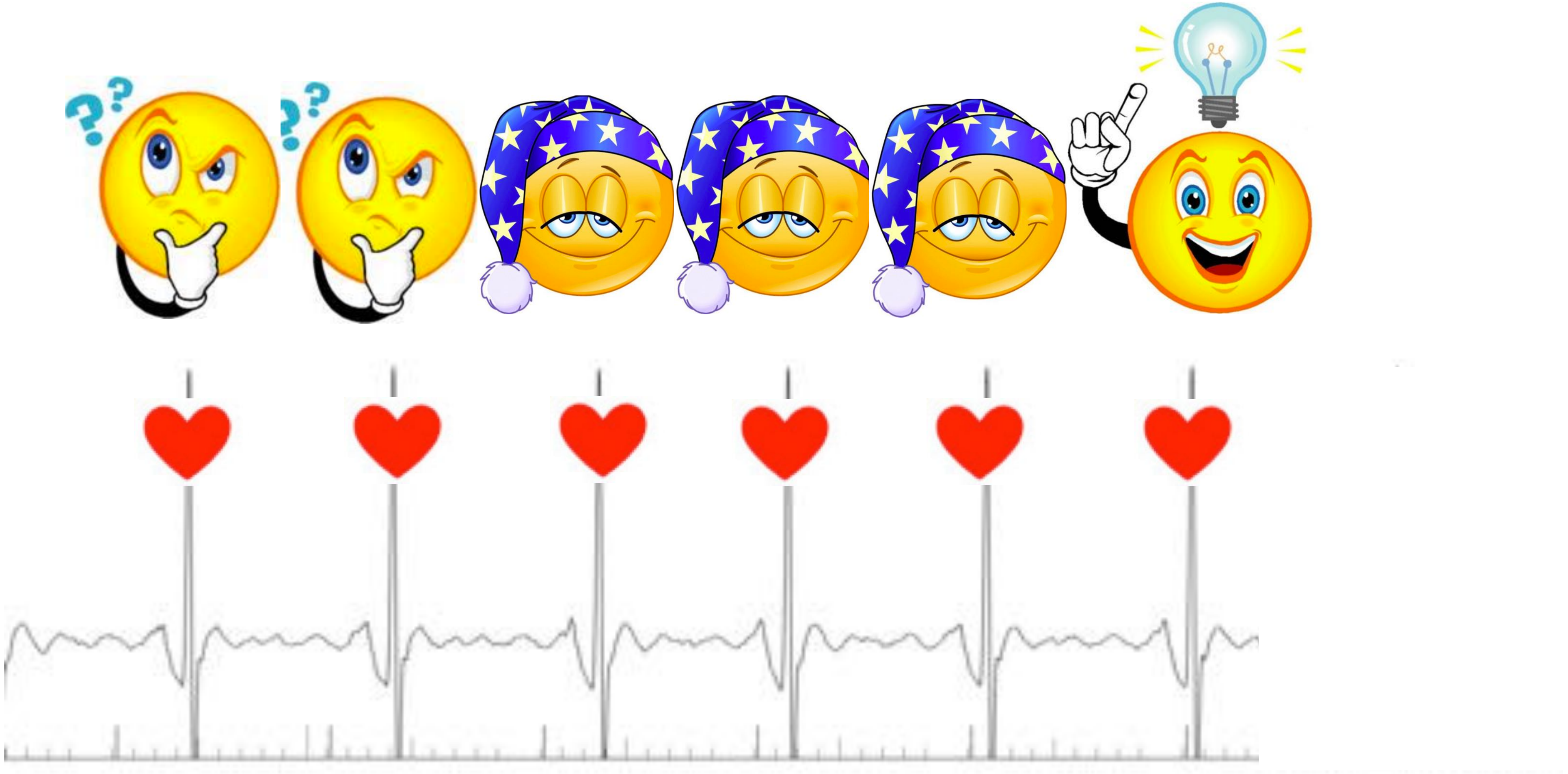
Smith et al, 2020, MedRxiv

Heartbeat counting task: assumption



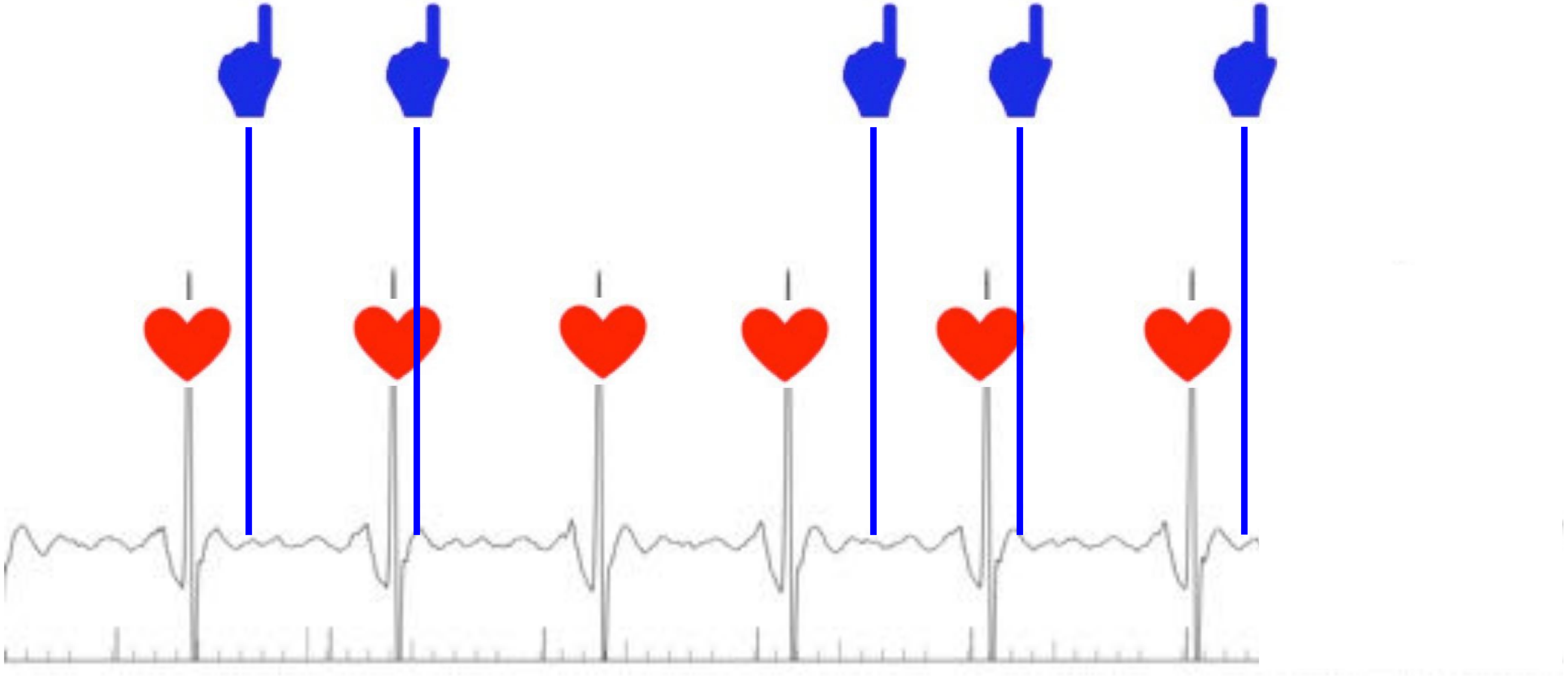
Cue “Start”	Attend to stimulus	Response: *“Five”*

Heartbeat counting task: reality?



Cue "Start"	Attend to stimulus	Response: *"Five"*

Heartbeat tapping captures real time behavior



Cue "Start"	**Attend to stimulus**	**Response:** Five taps

Heartbeat tapping task

- Three conditions:
  - 'Best guess' 
  - 'No guessing' 
  - 'No guessing' during inspiratory breath hold – ***respiratory perturbation*** (to increase afferent signal strength)

 + 

- Tone tapping – exteroceptive control

- Participants instructed to press a keyboard button in synchrony with their heartbeat
- Each condition 1 minute in duration

Self-report measures

- Directly **after** completing **each task condition**, individuals were asked the following using a visual analogue scale:
  - **“How accurate was your performance?”**
  - **“How difficult was the previous task?”**
  - **“How intensely did you feel your heartbeat?”**
- Each scale had anchors of **“not at all” and “extremely”** on the two ends. Numerical scores could range from **0 to 100**.

Computational modelling

- Our primary aims were to

    - 1) **demonstrate the sensitivity** of a novel Bayesian **computational approach** for measuring the precision weighting of interoceptive signals and prior expectations

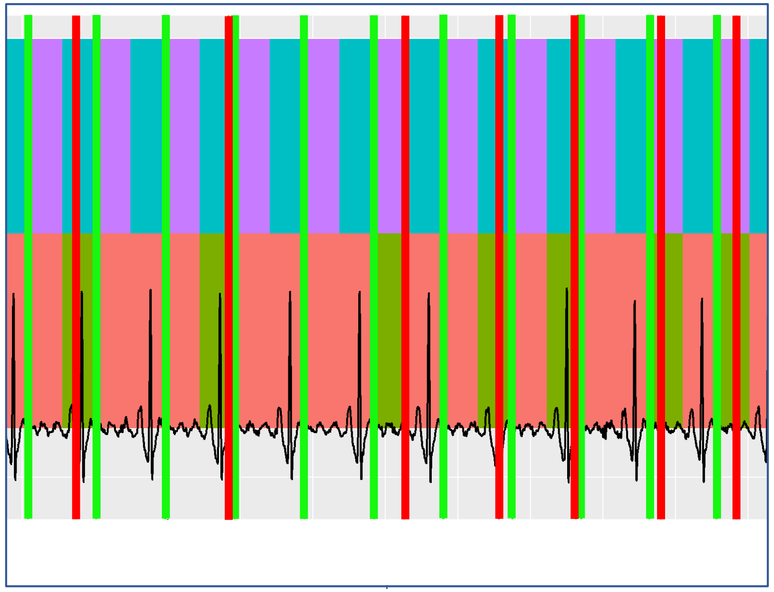
    - 2) test the hypothesis that patient groups show **lower interoceptive precision** weightings than HCs, **more precise prior expectations** than HCs, or **both**

    - 3) explore whether prior expectations and/or interoceptive precision is **abnormal in general or selectively** within resting or interoceptive perturbation conditions.

Participants: Mean (and standard deviation) for clinical and demographic variables.

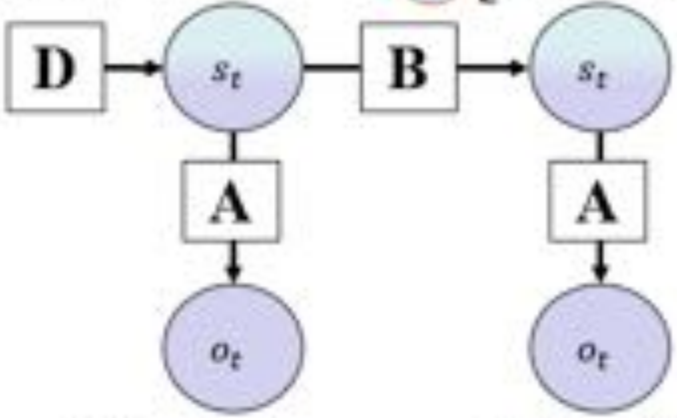
Individual difference variable	Healthy comparisons (N = 52)	Anxiety disorder (N = 15)	Depressive disorder (N = 69)	Depression + anxiety (N = 153)	Eating disorder (N = 14)	Substance use disorder (N = 131)	p-value
Age (years)	32.0 (11.1)	36.4 (10.0)	37.1 (11.8)	35.3 (11.2)	**27.4 (9.8)**	34.0 (8.9)	0.012
Sex	50% male	**33% male**	**30% male**	**26% male**	**14% male**	45% male	0.001
PHQ-9 - depression	0.8 (1.3)	7.5 (5.8)	13.5 (4.7)	13.1 (5.2)	12.9 (7.9)	6.7 (5.9)	<0.001
OASIS - anxiety	1.4 (1.9)	10.6 (2.2)	7.6 (3.3)	10.5 (3.1)	9.5 (4.9)	5.9 (4.8)	<0.001
DAST-10 - addiction	0.1 (0.3)	0.3 (0.5)	0.7 (1.7)	0.6 (1.1)	1.2 (2.6)	7.6 (2.1)	<0.001
Pulse Transit Time (seconds)	0.20 (0.02)	0.20 (0.01)	0.19 (0.01)	0.20 (0.02)	0.20 (0.02)	0.20 (0.02)	0.261
Body mass index	27.6 (5.5)	27.1 (6.0)	28.5 (5.5)	28.8 (5.5)	**22.3 (4.4)**	28.2 (4.6)	0.001

QC: removed 19 individuals for pulse taking; 3 individuals didn't complete the task; 13 individuals had poor EKG signals across all trials.
An additional 31 individuals were removed due to being outliers when performing the tone task (using Iterative Grubb's with $p < 0.01$).
Diagnosis verified via structured clinical interview using DSM-5 criteria, with groupings according to Aupperle et al. (2020) *JMIR Ment Health*



Blue = diastole
Purple = systole
Light Red = no tap
Dark Green = tap

Green vertical lines = R-wave + 200ms
Red vertical lines = tap location



$$
P(s_{t=1}) = \begin{array}{l} \\ \end{array}\begin{bmatrix}1\\0\\0\end{bmatrix}\begin{array}{l}\text{Start}\\ \text{No Heartbeat}\\ \text{Heartbeat}\end{array}
\qquad
P(s_{t=2}) = \begin{bmatrix}0\\P(nHB)\\P(HB)\end{bmatrix}
$$

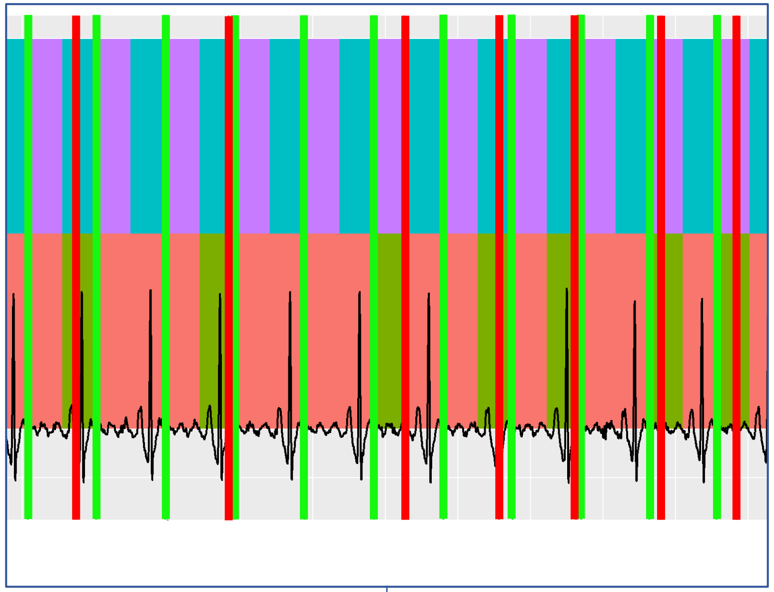
$$
\begin{array}{c|ccc|c}
 & \text{Start} & \text{No Heartbeat} & \text{Heartbeat} & s_t \\
\hline
\text{Start} & 0 & 0 & 0 & \\
\text{No Heartbeat} & 1 - pHB & 1 & 0 & s_{t+1} \\
\text{Heartbeat} & pHB & 0 & 1 &
\end{array}
$$

B = P(s_{t+1}|s_t)

$$
\begin{array}{l} \text{Start} \\ \text{Diastole} \\ \text{Systole} \end{array}\begin{bmatrix}1\\0\\0\end{bmatrix}
\qquad
\begin{array}{cc}
\begin{bmatrix}0\\1\\0\end{bmatrix} & \begin{bmatrix}0\\0\\1\end{bmatrix} \\
\text{Diastole} & \text{Systole}
\end{array}
$$

$$
\begin{array}{c|ccc}
 & \text{Start} & \text{No Heartbeat} & \text{Heartbeat} \\
\hline
\text{Start} & 1 & 0 & 0 \\
\text{Diastole} & 0 & IP & 1 - IP \\
\text{Systole} & 0 & 1 - IP & IP
\end{array}
$$

A = P(o_t|s_t)



IP = interoceptive precision
pHB = prior expectation for heartbeat

Blue = diastole
Purple = systole
Light Red = no tap
Dark Green = tap

Green vertical lines = R-wave + 200ms
Red vertical lines = tap location

Heartbeat perception:

$$\bar{s}_{t=1} = \boldsymbol{\sigma}\left(\frac{1}{2}(\ln \mathbf{D} + \ln \mathbf{B} \cdot s_{t+1}) + \ln \mathbf{A} \cdot o_t\right)$$

$$\bar{s}_{t=2} = \boldsymbol{\sigma}(\ln \mathbf{B}\, s_{t-1} + \ln \mathbf{A} \cdot o_t)$$

Model Variables

Model variable	General Definition	Model-specific specification
o_t	Observable outcomes at time t	Outcome modalities: 1. Diastole vs. systole
s_t	Hidden states at time t	Hidden state factors: 1. Feel heartbeat vs. no heartbeat
A matrix $p(o_t \mid s_t)$	A matrix encoding beliefs about the relationship between hidden states and observable outcomes (i.e., the probability that specific outcomes will be observed given specific hidden states).	Encodes beliefs about the relationship between felt heartbeats and diastole vs. systole. The precision of the relationship between heartbeats and diastole/systole was controlled by a parameter **IP**, which specified how much evidence systole provides for a heartbeat and how much evidence diastole provides for the absence of a heartbeat.
B matrix $p(s_{t+1} \mid s_t)$	A matrix encoding beliefs about how hidden states will evolve over time (transition probabilities).	Encodes **the prior expectation** that either a heartbeat or no heartbeat would occur on each trial, as controlled by a parameter pHB.
D vector $p(s_1)$	A matrix encoding beliefs about (a probability distribution over) initial hidden states.	Ensures the individual always begins in an initial starting state.

More complex learning model

$$b(heartbeats) = P(s_{t+1}|s_t) = \begin{bmatrix} 0 & 0 & 0 \\ 1 - pHB & 1 & 0 \\ pHB & 0 & 1 \end{bmatrix} \times b_0$$

$$b_t = b_{t-1} + \sum_t s_t \otimes s_{t-1}$$

- This just says that **prior expectations** for feeling a heartbeat **go up** after every time you **think you felt one**, and **vice-versa** when you **don't think you felt one**
- The larger b_0 is the **more slowly** you update prior expectations – **rigid priors**.

Final Model Parameters

- **b_0** – inverse learning rate (in learning model)
- **pHB** – prior expectations to feel a heartbeat (e.g., faster heart rate)

- The "raw" IP parameter values were transformed to correctly capture 2 distinct constructs of interest.

$$IP = |IP_{raw} - 0.5|$$

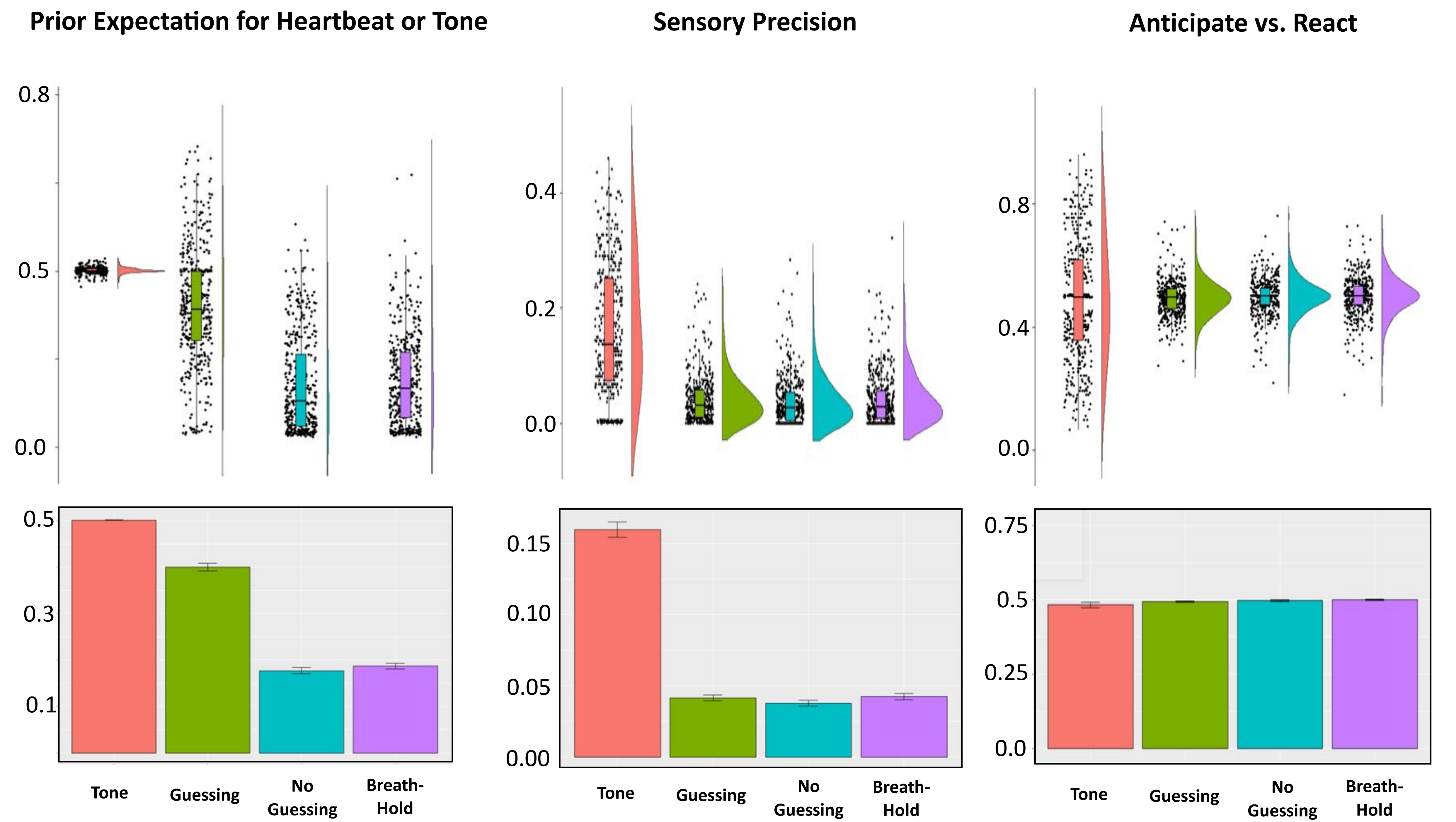
- This means that **IP** has a minimum value of 0 and a maximum value of 0.5. (reliable anticipatory or reactive tapping)

$$AvR = IP_{raw}$$

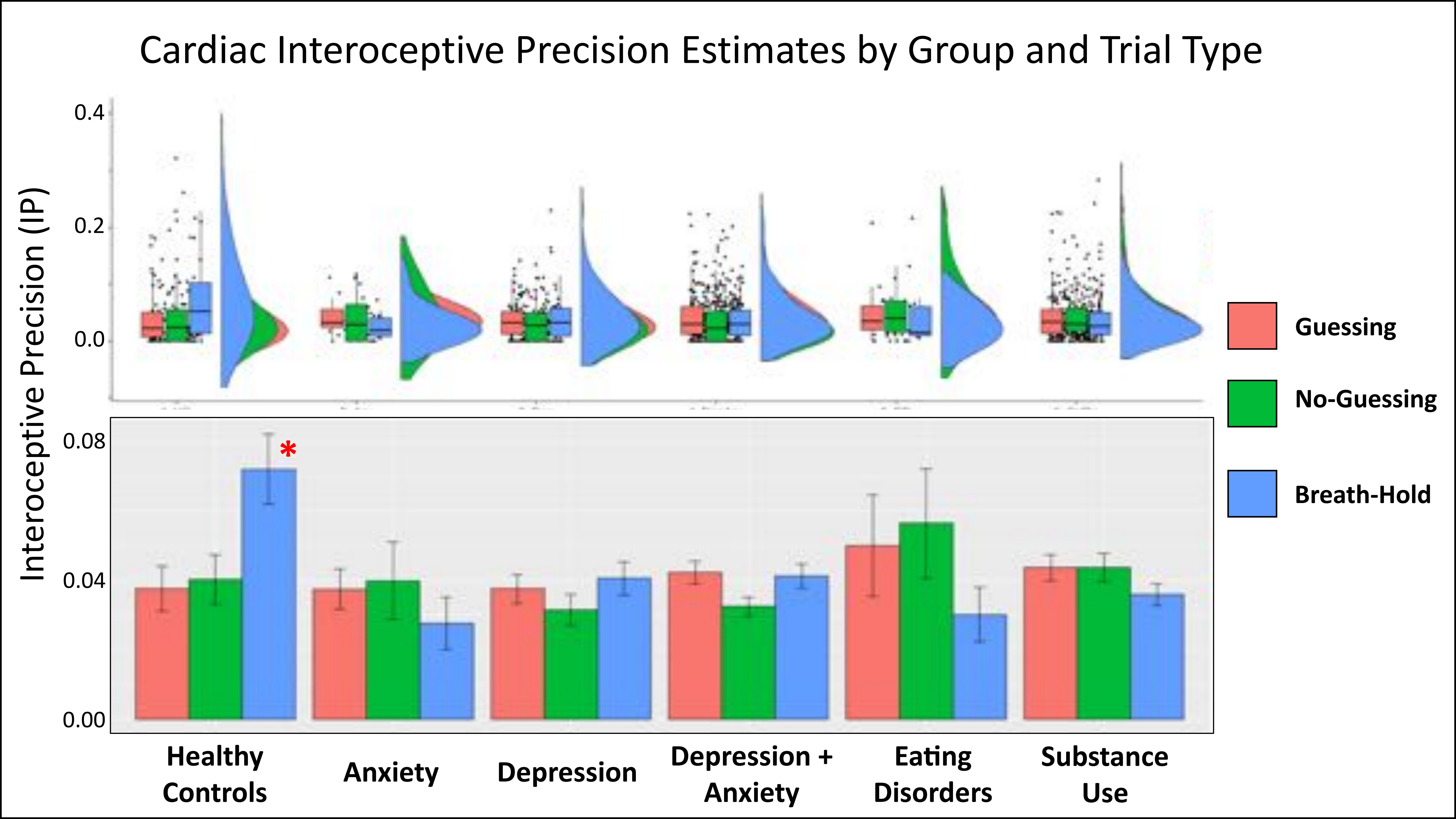
- Higher **AvR** values (> 0.5) thus indicated a stronger tendency to **reactively** tap in response to a heartbeat as opposed to tapping in an **anticipatory** fashion (< 0.5).

Model comparison

- **Overall, there was more evidence for the model without learning**
- The **"perception only" model was better** than the model that included learning prior expectations for the **no-guessing and breath-hold** conditions (protected exceedance probability = 1)
- There was **not a significantly better model for the guessing condition** (protected exceedance probabilities = .46 vs. .54, slightly favoring the learning model).
- The **learning model was better in the tone condition** (protected exceedance probability = 1).
- No group differences were observed when comparing model fits between groups.



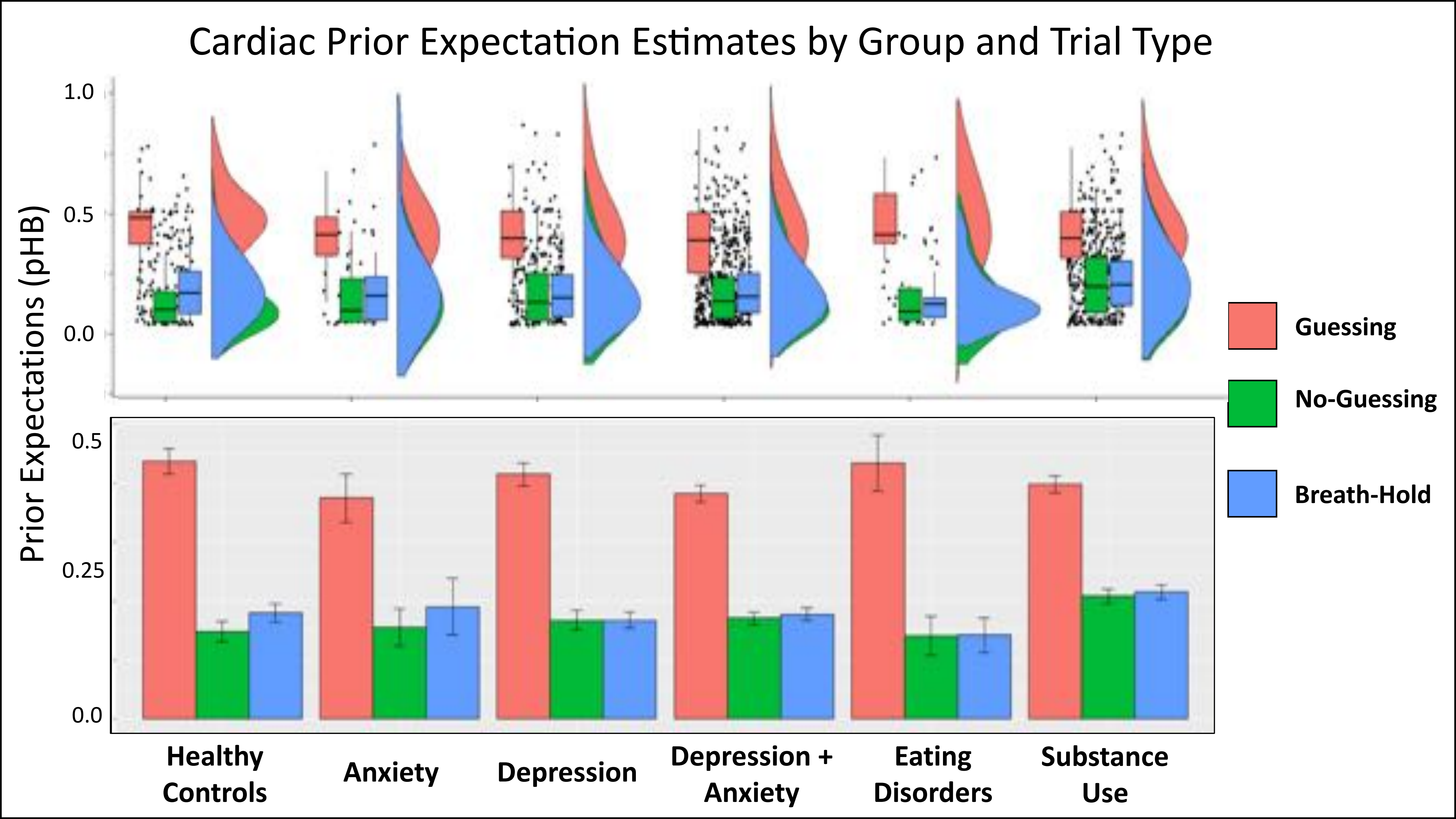
Prior Expectation for Heartbeat or Tone
Sensory Precision
Anticipate vs. React
0.8
0.5
0.0
0.4
0.2
0.0
0.8
0.4
0.0
0.5
0.3
0.1
0.15
0.10
0.05
0.00
0.75
0.5
0.25
0.0
Tone
Guessing
No Guessing
Breath-Hold
Tone
Guessing
No Guessing
Breath-Hold
Tone
Guessing
No Guessing
Breath-Hold



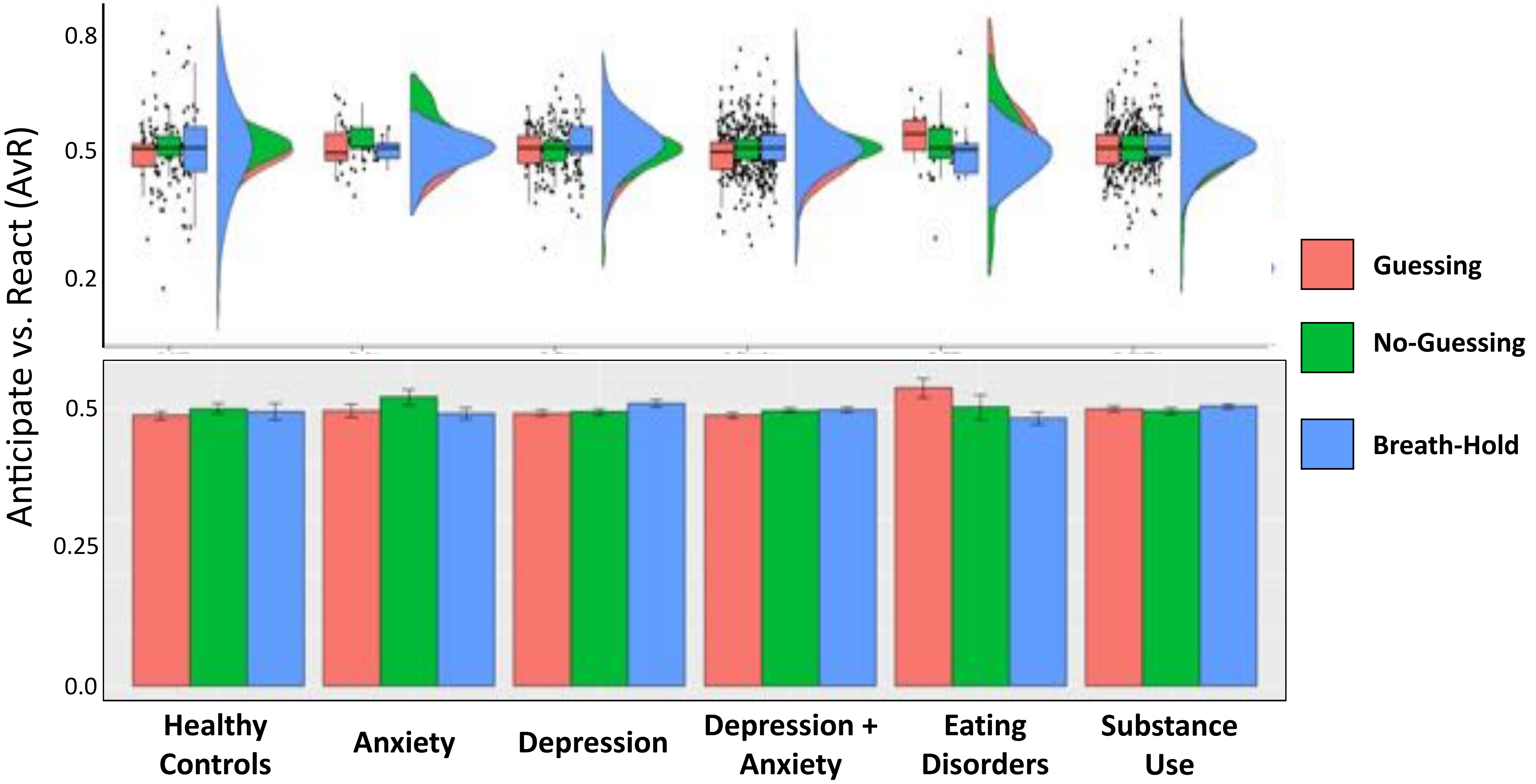
Cardiac Interoceptive Precision Estimates by Group and Trial Type
Interoceptive Precision (IP)
0.4
0.2
0.0
0.08
0.04
0.00
*
Guessing
No-Guessing
Breath-Hold
Healthy Controls
Anxiety
Depression
Depression + Anxiety
Eating Disorders
Substance Use

Group by condition ANOVAs (Interoceptive Precision)

- **Main effect of group** (*F(5,1273)* = 2.35, *p* = .04)
- **Group by condition interaction** (*F(10,1273)* = 3.10, *p* < .001);
- Post-hoc Tukey comparisons indicated:
  - **Greater IP in HCs than DEP/ANX** (*p* = .05) **and DEP** (*p* = .04)
  - **Greater IP in the breath-hold condition than in the guessing (*p* = .005) and no-guessing (*p* = .02) conditions in HCs**
    - but <u>not</u> in any of the other clinical groups
  - HCs had **greater IP** than ANX, DEP, DEP+ANX, and SUDs in the **breath-hold condition** (*p* = .04, *p* = .008, p = .001, and *p* < .001, respectively).
- The **group by condition interaction remained significant** (*F(10,1114)* = 2.7, *p* = .003) when also including age, sex, BMI, median PTT, precision within the tone condition, number of heartbeats (and it's interaction with condition), and medication status within the model.


Cardiac Prior Expectation Estimates by Group and Trial Type
Prior Expectations (pHB)
1.0
0.5
0.0
0.5
0.25
0.0
Guessing
No-Guessing
Breath-Hold
Healthy Controls
Anxiety
Depression
Depression + Anxiety
Eating Disorders
Substance Use

Anticipate vs. React Estimates by Group and Trial Type



Guessing

	PTT	# HBs	Difficulty	Confidence	Intensity	Age	BMI	Counting Accuracy
IP	-0.03	-0.02	-0.01	0.03	0.07	0.01	-0.03	0.22*
pHB	0.03	-0.13	-0.12	0.06	0.12	-0.12	0.03	0.09
AvR	0.02	-0.03	0	-0.07	-0.06	-0.01	-0.02	0.03

No Guessing

	PTT	# HBs	Difficulty	Confidence	Intensity	Age	BMI	Counting Accuracy
IP	-0.03	-0.09	-0.02	-0.08	0.24*	-0.03	-0.05	0.34*
pHB	-0.12	-0.04	-0.29*	0.16*	0.71*	0.01	0.03	0.95*
AvR	0.09	-0.08	0.05	-0.08	-0.15	-0.06	-0.05	-0.14

Breath-Hold

	PTT	# HBs	Difficulty	Confidence	Intensity	Age	BMI	Counting Accuracy
IP	-0.02	-0.06	-0.1	0.13	0.29*	-0.1	-0.03	0.31*
pHB	-0.03	0.03	-0.13	0.21*	0.67*	-0.14	0.02	0.87*
AvR	0.02	-0.03	0.03	-0.1	-0.14	0.01	0.02	-0.08

Tone

	PTT	# HBs	Difficulty	Confidence	Intensity	Age	BMI	Counting Accuracy
AP	-0.04	0.03	-0.08	-0.01	0.05	0	0.05	-0.02
pT	0	0.01	0.02	-0.07	-0.01	-0.02	0	0.24*
AvR	-0.08	0.04	-0.06	0.1	0.09	0.18*	0.09	0.05

Summary

- Cardiac interoceptive precision **at rest** was **equally poor** in HCs and psychiatric patients with depression, anxiety, substance use and eating disorders
- A breath-hold perturbation (aimed at amplifying afferent signal) **increased interoceptive precision in HCs** but <u>not</u> in any patient groups
- **Prior expectations** were modulated by task condition, but **did not differ** in the psychiatric patient groups
- **Learning** does <u>not</u> appear to be involved (likely due to poor signal)
- Anticipatory vs. reactive **strategies were not different** between groups
- The traditional **heartbeat counting accuracy** measure primarily **tracks prior expectations** about the heartbeat

Conclusion

- These computational modeling results suggest the possibility that individuals with depression, anxiety, eating, and substance use disorders **cannot update precision estimates** when afferent interoceptive signals change, at least with respect to the cardiac signal

- The inability to adjust sensory precision when signals from the body change could play a role in **visceral dysregulation** observed in psychiatric disorders during high arousal states

- Future directions:
    - Replication in an independent healthy sample
    - Replication in 2nd patient cohort of Tulsa 1000 dataset
    - Integrate the model with neural measurements
    - Examine influence of other physiological perturbations

How well do you understand the concept of interoception?

A. Not very well

B. A little

C. Moderately

D. Quite well

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