A confirmation bias in how humans actively sample sensory information

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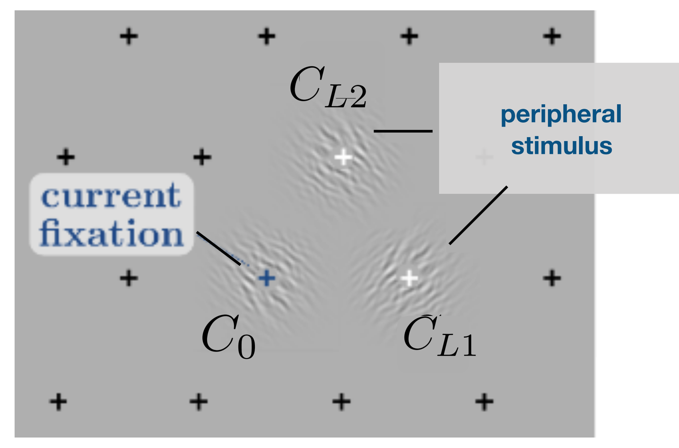
1 Introduction

- We interpret visual scenes by making **eye-movements** to different locations and accumulating corresponding evidence.
- A recent work[1] showed that humans make eye movements in a goal directed fashion following a **Bayesian Active Sensor (BAS)** algorithm when performing a categorization gaze contingent task.
- Other studies investigating temporal integration of information have shown that humans are often, but not always, biased to overweight early evidence ("primacy effect" or perceptual **confirmation bias (CB)**)[3,4].
- We recently showed perceptual CB could be explained by assuming that the brain performs **approximate inference in a hierarchical model in which expectations influence sensory inferences**. This gives evidence for CB in "covert" allocation of samples.[2]
- Our present study is a test of "overt" allocation of samples: **Are saccades biased to confirmatory or contradictory peripheral stimuli?**
- In our tasks, subjects incorporate **information from the periphery** to determine their saccade targets.

2 Gaze contingent orientation discrimination task

Task: The subject first fixates on a band-passed Gabor stimulus either oriented +45 degrees or -45 degrees while two other similar stimuli appear in the periphery. Subject is allowed to saccade and foveate on one of them to increase information about the "unclear" peripheral stimuli. After three such saccades, the subject has to report the most frequent orientation.



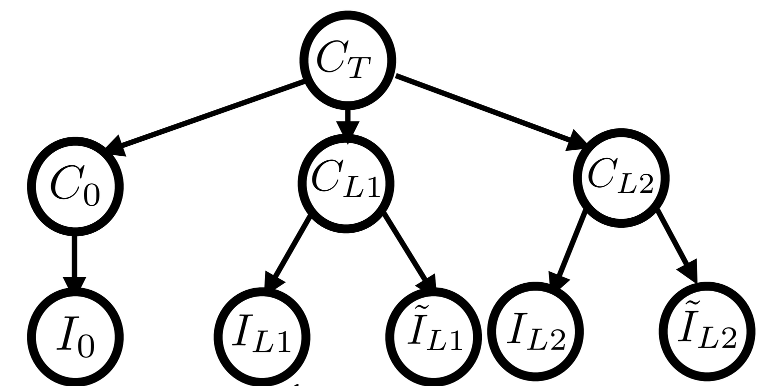
C_T = Category of trial I_0 = Image at fovea

C_0 = Category at fovea I_{L1} = Image at fovea location 1

C_{L1}= Category at location 1 $\tilde{I}_{L1}$ = Image at periphery location 1

C_{L2}= Category at location 2 I_{L2} = Image at fovea location 2

$\tilde{I}_{L2}$ = Image at periphery location 2



$$p(C_{L1}|C_T) = \begin{cases} C_T & \text{with } \pi \\ -C_T & \text{with } (1-\pi) \end{cases}$$

$$p(I_0|C_0) = \mathcal{N}(C_0, \sigma_0^2)$$
$$p(I_{L1}|C_{L1}) = \mathcal{N}(C_{L1}, \sigma_0^2)$$
$$p(\tilde{I}_{L1}|C_{L1}) = \mathcal{N}(I_{L1}, \sigma_{\text{ecc}}^2)$$
$$\mathcal{D} = \left\{I_0^{(1,\ldots,t)}, \tilde{I}^{(1,\ldots,t)}, \tilde{I}_{L1}^{(t+1)}, \tilde{I}_{L2}^{(t+1)}\right\}$$

Before making a saccade from foveated location 0, the Bayesian observer computes BAS score for location $L1$ and $L2$ [1] If $Score(L1) > Score(L2)$ then the ideal observer chooses to saccade to location $L1$ else they saccade to location $L2$. The BAS score has two components.

$$Score(L1) = \underbrace{\mathbb{H}[C_{L1}|\mathcal{D}]}_{\text{Component 1}} - \underbrace{\mathbb{E}_{p(C_T|\mathcal{D})}[\mathbb{H}[C_{L1}|C_T,\mathcal{D}]]}_{\text{Component 2}}$$

Degree of approximation of these components determines type and amount of bias in evidence selection.

$$\approx \mathbb{H}[C_{L1}|\mathcal{D}] - \frac{1}{s}\sum_{i=1}\mathbb{H}\left[C_{L1}|C_T^{(i)},\mathcal{D}\right]$$

$$= \mathbb{H}[C_{L1}|\mathcal{D}] - \frac{1}{s}\sum_{i=1}^{s}\left[-\sum_c p\left(C_{L1}=c|C_T^{(i)},\mathcal{D}\right)\log p\left(C_{L1}=c|C_T^{(i)},\mathcal{D}\right)\right]$$

$$= -\sum_c\sum_{C_T} p(C_{L1}=c, C_T|\mathcal{D})\log p\sum_{C_T}(C_{L1}=c, C_T|\mathcal{D}) - \frac{1}{s}\sum_{i=1}^{s}\left[-\sum_c p\left(C_{L1}=c|C_T^{(i)},\mathcal{D}\right)\log p\left(C_{L1}=c|C_T^{(i)},\mathcal{D}\right)\right]$$

$$\approx -\sum_c \frac{1}{s}\sum_{i=1}^{s} p\left(C_{L1}=c, C_T^{(i)}|\mathcal{D}\right)\log\frac{1}{s}\sum_{i=1}^{s}p\left(C_{L1}=c, C_T^{(i)}|\mathcal{D}\right) - \frac{1}{s}\sum_{i=1}^{s}\left[-\sum_c p\left(C_{L1}=c|C_T^{(i)},\mathcal{D}\right)\log p\left(C_{L1}=c|C_T^{(i)},\mathcal{D}\right)\right]$$

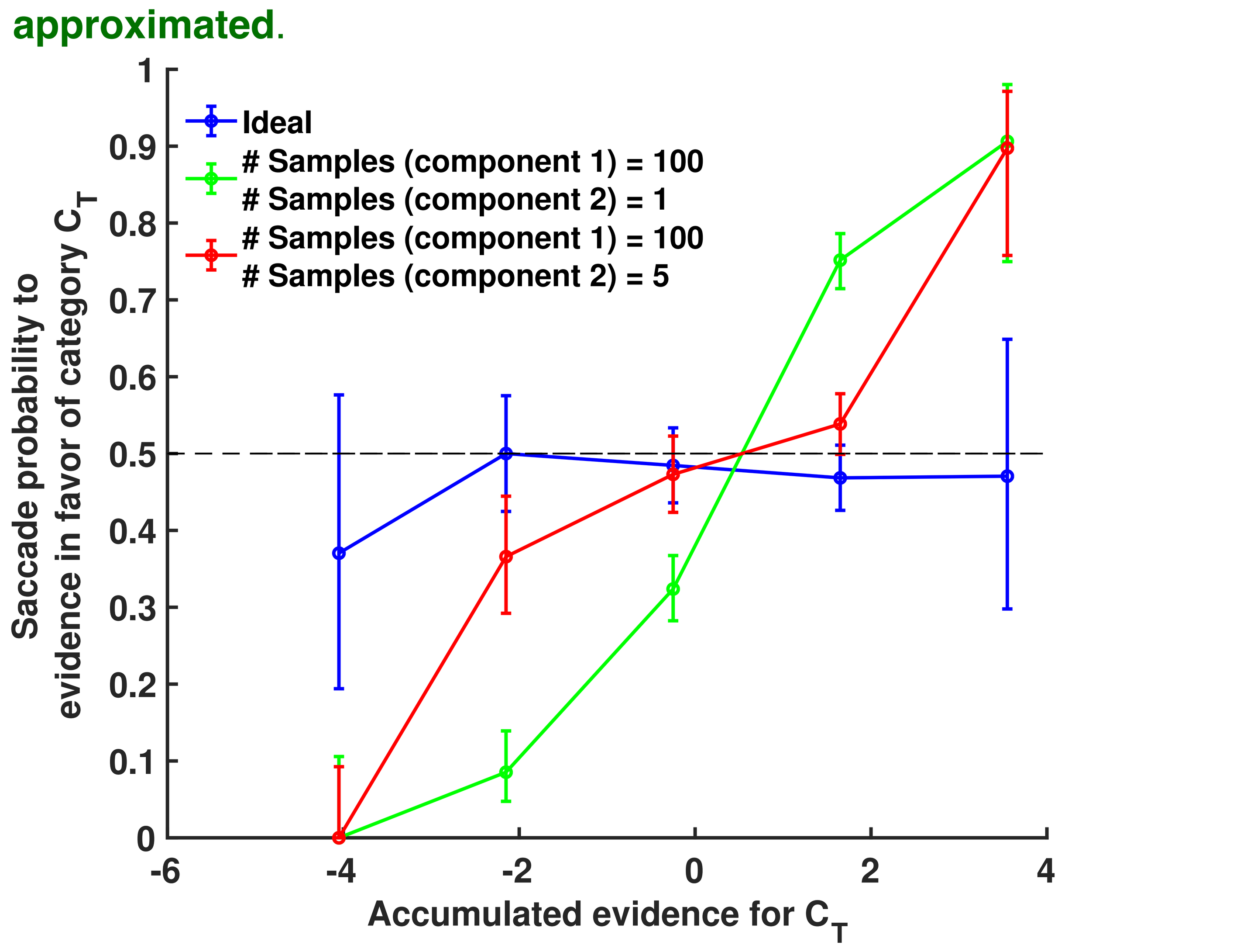
$$\text{where } C_T^{(i)} \sim p(C_T|\mathcal{D})$$

We draw samples of C_T to approximate Component 1 and Component 2. The lesser the number of samples, the stronger the approximation.

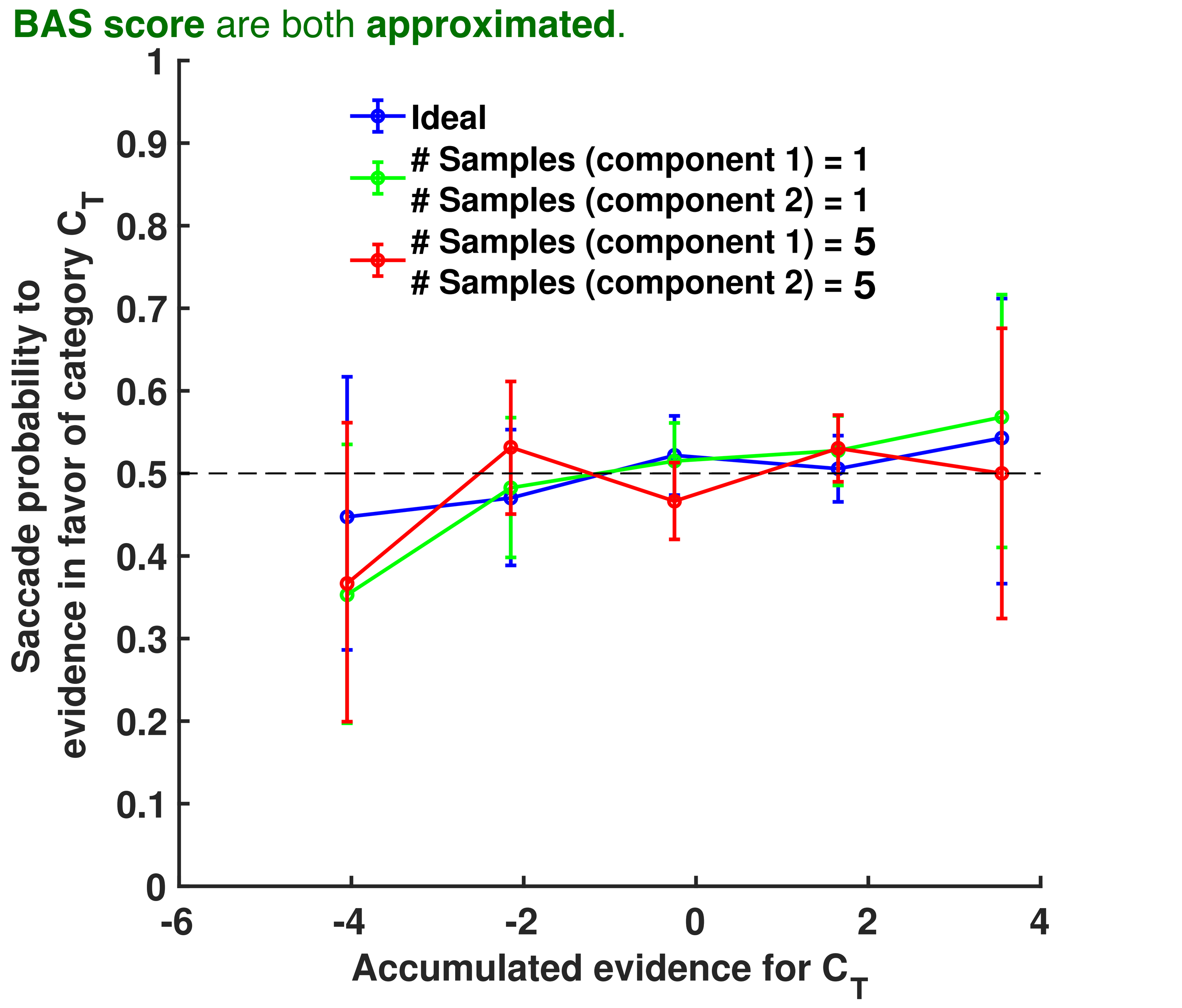
3 Hybrid Sampling Model

- The **BAS** score for a particular location is the **mutual information** between the category of the trial and the category at that location.
- The **BAS** score can be written as the **difference between total entropy and noise entropy** where component 1 **is the total entropy** and component 2 **is the noise entropy**.
- Component 1 is the **entropy over the category at the location L1** is likely to computed in a lower sensory area of the brain.
- Component 2 is the **conditional entropy over the category at the location L1 conditioned on the trial category**. Since this would require marginalizing over the belief about the trial category, this is more likely to be computed in higher sensory areas.
- We hypothesize that lower sensory areas have a faster sampling time and hence draw more samples to compute component 1 as compared to component 2.

Observation 1: Bias to saccade to evidence in favor of accumulated evidence exists only when **Component 2** of **BAS score** is **approximated**.



Observation 2: No bias when **Component 1** and **Component 2** of **BAS score** are both **approximated**.



5 Conclusion

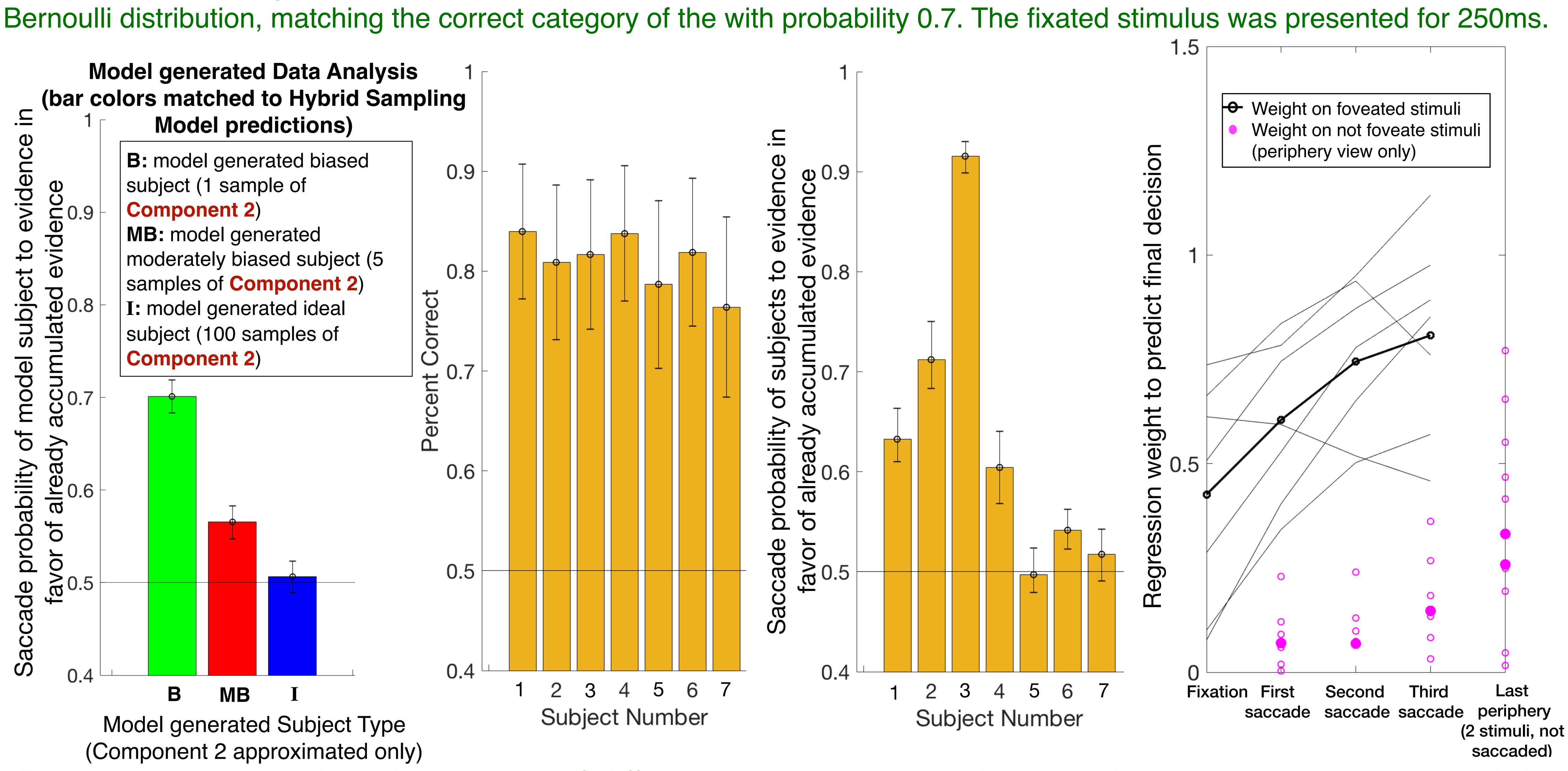
- We investigate whether eye-movements are biased when sampling new information in a visual perceptual decision-making.
- We test this in two tasks to infer the most frequent category of a trial:
  - a gaze-contingent stimulus display
  - a more natural scenario of freely moving eyes
- In both experiments we find some evidence that integrated information from already fixated locations drive eye movement such that the next fixation is at a location whose evidence confirms the belief about the correct category based on evidence already integrated.

References

[1] Scott Cheng-Hsin Yang, Mate Lengyel, Daniel Wolpert (2016) Active sensing in the categorization of visual patterns, eLife
[2] Lange, R. D., Chattoraj, A., Beck, J., Yates, J., & Haefner,R. (2018). A confirmation bias in perceptual decision-making due to hierarchical approximate inference, bioRxiv
[3] Kiani, R., Hanks, T. D., & Shadlen, M. N. (2008). Bounded integration in parietal cortex underlies decisions even when viewing duration is dictated by the environment. The Journal of neuroscience
[4] Nienborg, H., & Cumming, B. G. (2009). Decision-related activity in sensory neurons reflects more than a neuron's causal effect. Nature

4 Experimental observations

Study 1: Gaze contingent orientation discrimination task (shown in 2).Orientation of each stimulus was drawn from a Bernoulli distribution, matching the correct category of the with probability 0.7. The fixated stimulus was presented for 250ms.



Result 1: For saccades when stimuli of different orientation were shown in the periphery, we computed the subject's probability of making a saccade to a stimulus whose orientation agreed with the orientation of the majority of foveated stimuli so far. Controlling for base rates we found that subjects were more likely to saccade to a stimulus whose orientation matched that believed to be the most frequent orientation in that trial.

Study 2: Subject sees stationary stimuli of 18 black ellipses on gray background (some vertical and some horizontal) and is allowed to make eye-movements freely for 1.5 secs before choosing which orientation is most frequent.

Result 2: Subjects were systematically biased to be more likely to make saccades to ellipses whose orientation agreed with their accumulated evidence at that point in time.