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# Prior probability and feature predictability interactively bias perceptual decisions

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## ABSTRACT

Anticipating a forthcoming sensory experience facilitates perception for expected stimuli but also hinders perception for less likely alternatives. Recent neuroimaging studies suggest that expectation biases arise from feature-level predictions that enhance early sensory representations and facilitate evidence accumulation for contextually probable stimuli while suppressing alternatives. Reasonably then, the extent to which prior knowledge biases subsequent sensory processing should depend on the precision of expectations at the feature level as well as the degree to which expected features match those of an observed stimulus. In the present study we investigated how these two sources of uncertainty modulated pre- and post-stimulus bias mechanisms in the drift-diffusion model during a probabilistic face/house discrimination task. We tested several plausible models of choice bias, concluding that predictive cues led to a bias in both the starting-point and rate of evidence accumulation favoring the more probable stimulus category. We further tested the hypotheses that prior bias in the starting-point was conditional on the feature-level uncertainty of category expectations and that dynamic bias in the drift-rate was modulated by the match between expected and observed stimulus features. Starting-point estimates suggested that subjects formed a constant prior bias in favor of the face category, which exhibits less feature-level variability, that was strengthened or weakened by trial-wise predictive cues. Furthermore, we found that the gain on face/house evidence was increased for stimuli with less ambiguous features and that this relationship was enhanced by valid category expectations. These findings offer new evidence that bridges psychological models of decision-making with recent predictive coding theories of perception.

## 1. Introduction

Through past experience we are able to improve our internal model of the world and, consequently, our ability to anticipate, perceive, and interact with relevant stimuli in our environment. Indeed, there is a growing body of evidence to suggest that the brain proactively facilitates perception by constructing feature-level models or templates of expected stimuli (Clark, 2013; Summerfield & Egner, 2009). Neural correlates of predictive stimulus templates have been observed in visual (Jiang, Summerfield, & Egner, 2013; Kok, Failing, & de Lange, 2014; Summerfield et al., 2006; White, Mumford, & Poldrack, 2012), auditory (Chennu et al., 2013), somatosensory (Carlsson, Petrovic, Skare, Petersson, & Ingvar, 2000), and olfactory (Zelano, Mohanty, & Gottfried, 2011) cortex, highlighting feature prediction as a fundamental property of perception. It follows that feature-level predictions are compared with incoming sensory signals to determine a match between the expected and observed inputs. Thus, the extent to which expectations influence perception should depend, not only on the prior probability of a stimulus, but also the predictability of its content as well as the overlap in expected and observed features. For example, general expectations of encountering an animal are less informative about the forthcoming sensory experience than say, expecting to be greeted at the door by a familiar family pet. In the latter case, the set of predictable sensory features is constrained in comparison with the limited predictability afforded by anticipating any animal at all. However, it is presently unclear how feature-level uncertainty influences the underlying dynamics of perceptual expectation and decision-making.

Behaviorally, prior expectations bias the speed and accuracy of perception. When incoming sensory information is consistent with prior knowledge, stimuli are recognized more swiftly and

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with greater precision, whereas performance suffers when prior beliefs are contradicted by observed evidence (Carpenter & Williams, 1995; Król & El-Deredy, 2011a, 2011b; Puri & Wojciulik, 2008). Formal theories of perceptual decision-making, such as the drift-diffusion model, are centered around the assumption that recognition judgments are produced by sequentially sampling and accumulating noisy evidence to a decision criterion (Gold & Shadlen, 2007; Ratcliff, 1978). When no prior information is available, the distance to the decision criterion is the same for alternative choices and the rate of evidence accumulation is determined solely by the strength of the observed signal (Fig. 1A). However, access to advance knowledge such as the prior probability of alternative outcomes, may be leveraged to bias performance in favor of one choice over the other. One strategy is to preemptively increase the baseline evidence for the expected choice, reducing the amount of evidence that must be sampled to reach the corresponding criterion (Fig. 1B, top) (Edwards, 1965; Link & Heath, 1975; Leite & Ratcliff, 2011; Mulder, Wagenmakers, Ratcliff, Boekel, & Forstmann, 2012). Alternatively, prior knowledge may be used to dynamically weight incoming evidence, accelerating evidence accumulation for the more probable outcome (Fig. 1B, bottom) (Cravo, Rohenkohl, Wyart, & Nobre, 2013; Diederich & Busemeyer, 2006). Traditionally, baseline and rate hypotheses have been framed as alternative explanations of decision bias. However, converging behavioral and neurophysiological evidence now suggests that expectations may recruit both mechanisms (Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Diederich & Busemeyer, 2006; Hanks, Mazurek, Kiani, Hopp, & Shadlen, 2011; Van Ravenzwaaij, Mulder, Tuerlinckx, & Wagenmakers, 2012).

While diffusion models have provided valuable insights into the dynamics of perceptual judgment, they are agnostic about the exact sources of expectation bias and the stage of information processing at which prior knowledge is integrated with sensory evidence. Recent progress has come from tracking neural activity as human and animal subjects anticipate and categorize noisy perceptual stimuli. These studies have found compelling evidence that expectations bias sensory representations both prior to and during evidence accumulation via recurrent communication between early feature-selection and higher-order control regions. For instance, human neuroimaging studies have detected anticipatory signals or “baseline shifts” in sensory regions that are selective for expected stimuli (Esterman & Yantis, 2010; Kok et al., 2014; Shulman et al. 1999) as well as enhanced contrast between early target and distractor representations (Jiang et al., 2013; Kok, Jehee, & de Lange, 2012). Hierarchical models of perception, such as predictive coding, propose that these early sensory modulations represent a feature-level template of the expected stimulus, generated by top-down inputs from higher-order regions that encode more abstract predictions (i.e., category probability). The predictive template is updated to reflect each sample of evidence until uncertainty is sufficiently minimized and a decision can be made. In the event of a match, top-down gain is amplified to accelerate evidence accumulation and speed the decision, whereas mismatches are associated with greater reliance on bottom-up information and slower decision times, suggesting sensory gain is lowered to allow more evidence to be sampled (Summerfield & Koechlin, 2008).

Indeed, the neural correlates of perceptual expectations (discussed above) during pre- and post-stimulus epochs bear a striking resemblance to the prior and dynamic bias mechanisms proposed by sequential sampling models. More importantly though, these findings imply that the influence of prior knowledge is conditional on the precision at which abstract (i.e., categorical) expectations are mapped onto incoming evidence at the feature level. Thus, the effect of prior knowledge on the mechanisms of decision bias should reflect two critical bits of information – uncertainty in the features of the expected category as well as the categorical ambiguity of the observed features. Moreover, each of these sources of uncertainty is intuitively mapped to a distinct stage of the decision process, with uncertainty in the expected features influencing pre-sensory evidence and stimulus ambiguity affecting post-sensory evidence accumulation. The latter has been confirmed in a recent study showing that the representational distance between a stimulus and a discriminant category boundary in feature space could be used to predict RT, and furthermore, that this relationship could be explained by adjusting the drift-rate in a sequential sampling model (Carlson, Ritchie, Kriegeskorte, Durvasula, & Ma, 2013). Compared to stimuli with more ambiguous features, located closer to the category boundary, stimuli represented further away were categorized more rapidly due to a higher drift-rate on decision evidence (i.e., faster rate of evidence accumulation). However, it remains unclear how prior knowledge influences this relationship and how uncertainties in predicted and observed stimulus features interact during perceptual decision-making (see Bland and Schaefer (2012) for review).

We investigated these questions by fitting alternative diffusion models to behavioral data obtained in a probabilistic face/house discrimination task. Faces and houses were strategically chosen for

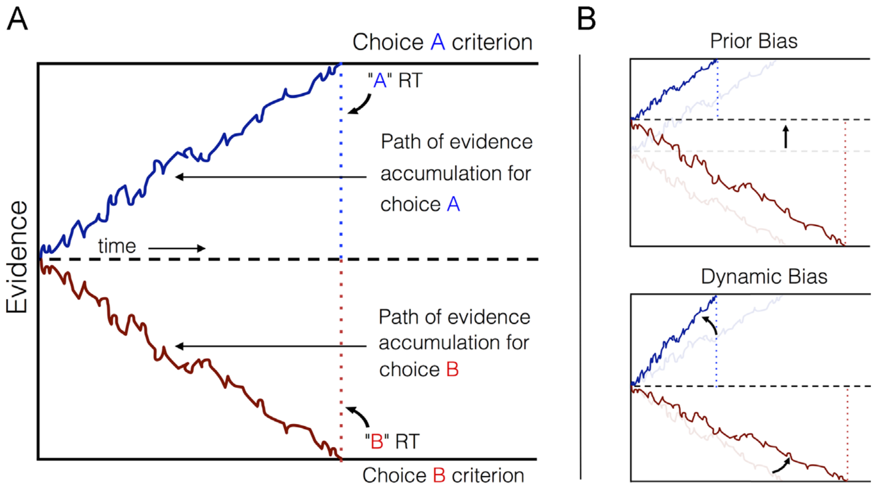

**Fig. 1.** Schematic of Drift-Diffusion Model. (A) The unbiased diffusion model shows two decisions for equal strength “A” (blue) and “B” (red) stimuli. Blue and red dotted lines mark the reaction time for each choice, equal for “A” and “B” decisions in this scenario. (B) Bias mechanisms. Prior Bias Model (PBM), the starting-point is shifted toward more probable boundary, decreasing criterion for expected choice (“A”) and increasing criterion for the alternative (“B”). Dynamic Bias Model (DBM), prior probability increases the slope of accumulation for the expected choice (“A”) and decreases slope for the alternative (“B”).