Complex adaptive internal model subserves perceptual sequential decision making

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Abstract: Despite recent findings of sequential effects in perceptual serial decision making (SDM) (Chopin & Mamassian 2012; Fischer & Whitney 2014), SDM is typically investigated under the assumption that the decisions in the sequence are independent or at most, are influenced by a few previous trials. We set out to identify the true underlying internal model of event statistics that drives decision in SDM by investigating and modeling a set of novel sequential 2AFC visual discrimination tasks by humans and rats. Participants solved the same decision task across trials, but experienced one shift in baseline appearance probabilities of noisy stimuli during the experiment. We found non-trivial interactions between short- and equally strong long-term effects guiding evidence accumulation and decisions in such SDM. These interactions could elicit paradoxical and long-lasting net serial effects, for example, a counterintuitive negative decision bias towards the recently less frequent element. Our findings cannot be explained by previous models of SDM that either assume a sequential integration of prior evidence, presume an implicit compensation of discrepancies between recent and long-term summary statistics, or adjust learning rates of those statistics at change points. To provide a normative explanation for the empirical data, we developed a hierarchical Bayesian model that could simultaneously represent the priors over the appearance frequencies and a potentially non-uniform noise model over the different stimulus identities. The results of simulations with the model suggest that humans are more disposed to readjust their noise model instead of updating their priors on appearance probabilities when they observe sudden shifts in the input statistics of stimuli. In general, regardless of the simplicity of the decision task, humans automatically utilize a complex internal model during SDM and adaptively alter various components of this model when detecting sudden changes in the conditions of the task.

Experimental design: In three experiments, participants performed a chain of about 500 2AFC perceptual decisions split to 200 training trials with feedback, and a test phase (without FB) to decide which of the two abstract shapes corrupted with varying amount of noise was presented in each trial (Fig1A). The appearance probabilities (AP) of shapes were the same during the test (65% for the frequent shape) in all experiments, while in the training blocks, it was either 65% (Exp. 1), 75% (Exp. 2) or 50% (Exp. 3) (Fig1B).

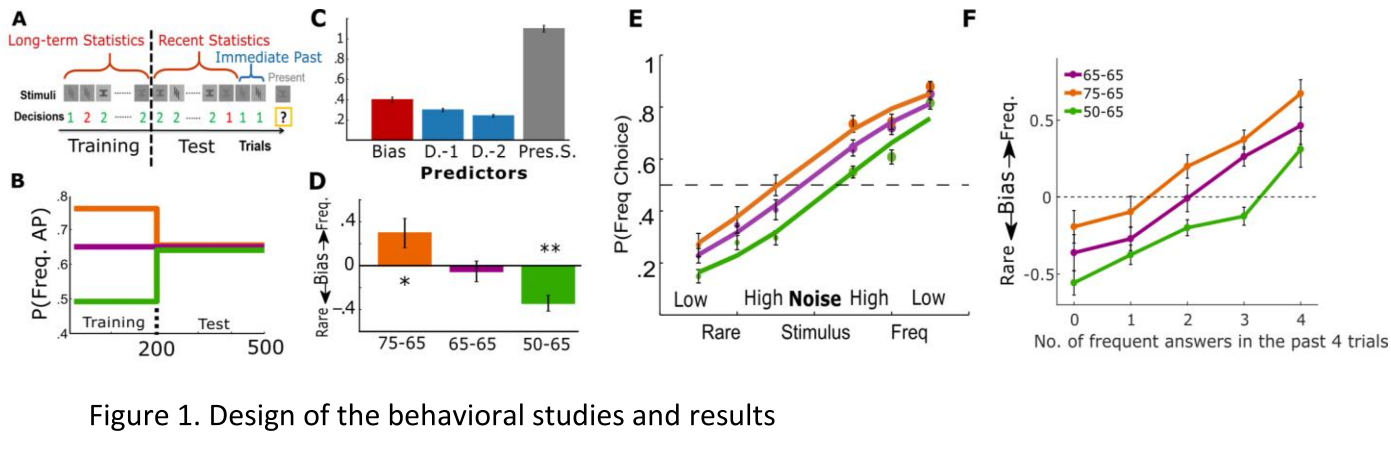

Figure 1. Design of the behavioral studies and results

Behavioral results: AIC-based model comparison of logistic regression models revealed that the best fitting model combined the previous two decisions and a long-term bias to make the present prediction. The standardized logistic regression weight of the bias was larger than those of the other two factors and smaller only to that of the presented stimulus (Fig1C). Across the entire test phase, there was a strong dependence of the momentary decisions on the difference between APs in the training and test blocks ranging from strong positive to strong negative bias across experiments (Fig1D) also showing up as a clear shift in the psychometric function (Fig1E). The strong negative bias in Exp 3 where 50% AP during training was followed by 65% AP for the frequent element during test means that, throughout the test, participants showed a clear preference for choosing the locally *rare* element when the stimulus was ambiguous despite seeing more frequent shapes in the preceding 10-100 trials [$t(20)= -4.78$, $p=0.00011$]. These results were replicated with Gabor stimuli and using orientation discrimination task with humans, and brightness discrimination task using rats. Meanwhile, short-term effects of the previous four trials generated a positive bias independent of the long-term effects (Fig1F).

Hierarchical Bayesian modeling: The basic generative model of the ideal SDM consists of x_t the observed parameter, x_t* binary shape identity, γ_t noise parameter, and p_t latent parameter (Bernoulli rate) representing the event statistics (Fig2A, structure linked by black arrows). This model fails to capture any across-trial effects. Recent hierarchical extensions of this basic model add λ_t change-point hyper parameter that detects changes in the conditions and enables adjustments in p_t accordingly (Fig2A, green arrow). Different versions of this extension fail to capture our results for different reasons. The Chopin & Mamassian model (2012) requires local negative biases for their proposed compensation mechanism between long-term history and recent observations, but our participants show local positive effects instead. The Nassar et al. (2010) and Gallistel et al (2014) models are not able to create a scenario where p_t changes produce negative bias in response to a 50%-to-65% AP change. In contrast to these models focusing exclusively on parameters of the tasks statistics, we implemented a normative hierarchical Bayesian model that represents the distribution over perceptual properties and event probabilities on the different levels of hierarchy as equally important factors, and separates out independent short-term effects (Fig2A, red and blue arrows). Crucially, the model allows for different noise distribution over the two target shapes (Gaussians with different μ and equal σ) if needed. The current decision is defined as a weighted combination of the posterior probabilities and the short-term serial effects.

Simulation results: Following the logic of cognitive tomography (Houlsby et al. 2013), we inferred the model parameters for each subject, and using these parameters, replicated the measures of Fig1EF. Using model selection, we found that implementing a negative bias on the event probabilities vs. two asymmetric noise-models at the perceptual properties was equally viable computational solutions. As at present time, there exists no computationally justifiable model for adjusting event biases to the paradoxical negative direction, we explored the asymmetric noise model option (Fig2A, red arrows), and found a convincing agreement between simulation and empirical results (Fig2BC). We conclude that in uncertain perceptual conditions, even when the true event probabilities at a higher level of the representational hierarchy change, while humans detect this change, they might have insufficient evidence of the nature the change, and prefer to adapt their lower level perceptual variables of their complex internal model.

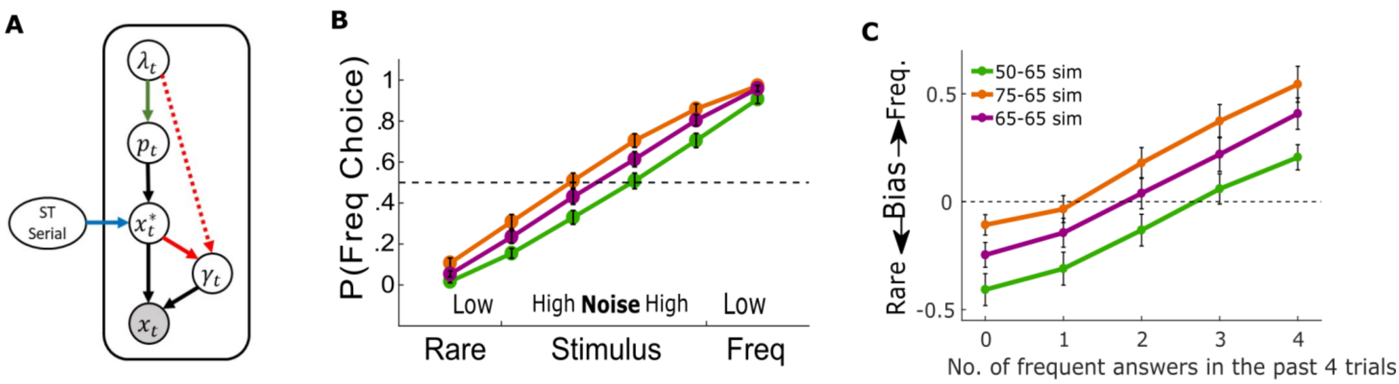

Figure 2. The generative models of SDM and fitting results