Decreasing sensory noise lowers metacognitive efficiency

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Abstract:

Visual metacognition is the ability to employ confidence ratings in order to predict the accuracy of one's perceptual decisions. Researchers have developed a number of paradigms to manipulate observers' overall confidence, independent of overall accuracy, but it is unclear how visual metacognitive efficiency can be affected. Here we show that a hierarchical model of confidence generation makes a counterintuitive prediction: metacognitive efficiency has a positive relationship with the level of sensory noise. In other words, decreasing trial-to-trial sensory noise is predicted to lower metacognitive efficiency. To test this prediction, we used a perceptual learning paradigm to decrease the amount of sensory noise. In Experiment 1, seven days of training led to significant decrease in noise but also a decrease in metacognitive efficiency. Experiment 2 showed the same effect in a brief 100-trial learning in each of two different tasks. Finally, in Experiment 3, we experimentally manipulated stimulus contrast to increase sensory noise and observed a corresponding increase in metacognitive efficiency. Our findings demonstrate the existence of a robust positive relationship between sensory noise and visual metacognition. These results provide strong support for our hierarchical model of confidence generation and demonstrate that one can directly manipulate metacognitive efficiency.

Keywords: confidence; perceptual decision making; metacognition; sensory processing; decision modeling

Introduction and Model

While, most research assumes that confidence and accuracy are based on the same sensory information, recent evidence points towards a hierarchical organization where confidence ratings are corrupted with additional noise (De Martino, Fleming, Garrett, & Dolan, 2013). A model with such hierarchical architecture (Figure 1) makes a previously unrecognized and untested prediction: that lowering sensory noise leads to lower metacognitive efficiency (measured as M_{ratio}; Maniscalco and Lau, 2012). Intuitively, the prediction holds because higher levels of sensory noise make the later metacognitive noise comparatively less damaging to the quality of the confidence ratings. To test this prediction, we conducted three experiments each manipulating sensory noise in a different way.

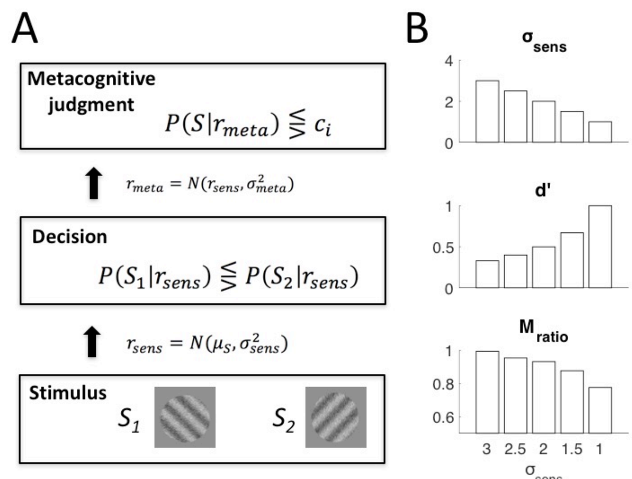

Figure 1: Hierarchical model of confidence. A. Each stimulus category gives rise to a sensory response r_{sens} that is used for the decision. The metacognitive judgment is made using an internal response r_{meta} that is corrupted by additional noise. B. This hierarchical model predicts that as sensory noise σ_{sens} decreases, sensitivity d' increases but metacognitive efficiency M_{ratio} decreases.

Experiment 1

To test the counterintuitive prediction that decreasing sensory noise leads to lower metacognitive efficiency, we employed a perceptual learning paradigm. Twelve subjects participated in 7-day training on a visual task. Figure 2 shows that learning resulted in a sensory noise decrease (t_{11}=5.17, p=.0003; Figure 2A), leading to corresponding increases in d' (t_{11}=5.48, p=.0002; Figure 2B) and confidence (t_{11}=2.43, p=.034; Figure 2C). Critically, as predicted by our model, metacognitive efficiency M_{ratio} decreased significantly (t_{11}=3.06, p=.011; Figure 2D) over the course of training, confirming the positive relationship between sensory noise and metacognitive efficiency.

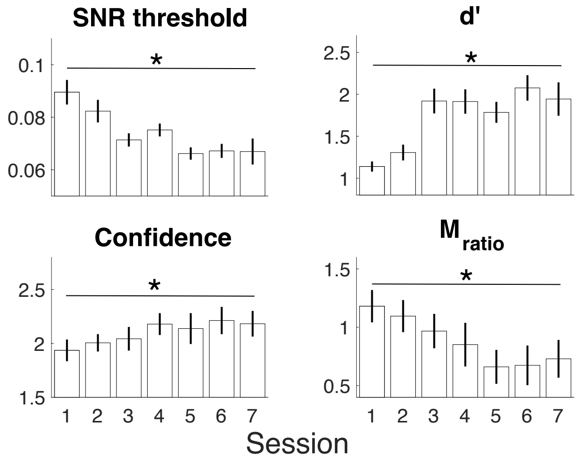

Figure 2: Experiment 1 results. Learning-induced decrease of sensory noise (as measured by the signal-to-noise ratio, SNR) leads to a decrease in M_{ratio}.

Experiment 2

We further extended the results from Experiment 1 by showing that the same effect occurs on a much shorter timescale of learning. 178 subjects performed 100 trials of two tasks: fine discrimination on high-contrast Gabors and coarse discrimination of low-contrast Gabors. As in Experiment 1, over the course of learning, both tasks showed a significant increase in sensitivity d' (low contrast task: p=9.1e-08; high contrast task: p=.01) but a decrease in M_{ratio} (low contrast task: p=1.1e-10; high contrast task: p=.01; Figure 3).

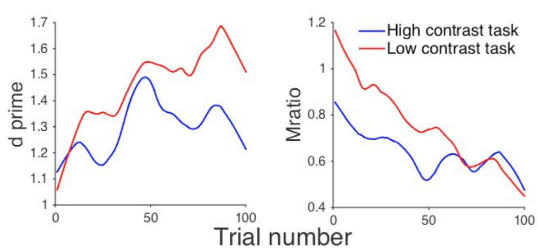

Figure 3: Experiment 2 results. Short, 100-trial learning led to a significant increase in d' (left) but a decrease in M_{ratio} (right) for both tasks.

Experiment 3

Finally, we further tested our model in Experiment 3 by experimentally manipulating the level of sensory noise. Twelve subjects performed 4,200 trials each over three days of testing. We constructed four conditions each consisting of increasingly higher variability in stimulus contrast (thus inducing higher level of trial-to-trial sensory noise). As predicted by our model, increasing contrast variability decreased d' (t_{11}=4.52, p=.0009) but increased M_{ratio} (t_{11}=6.21, p = .00007; Figure 4).

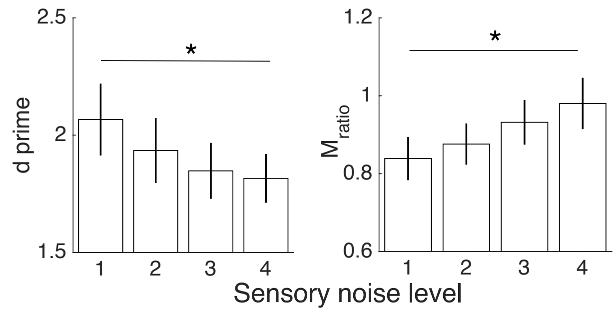

Figure 4: Experiment 3 results. Experimentally increasing sensory noise by increasing trial-to-trial variability of contrast levels leads to a decrease in d' (left) but increase in M_{ratio} (right).

Conclusion

We found a surprising but extremely robust positive relationship between the level of sensory noise and metacognitive efficiency. This relationship was predicted by our computational model that posits a hierarchical organization of information flow for perceptual decisions and confidence. Beyond predicting the qualitative effects of our various manipulations, our model is also able to quantitatively fit the data (not shown here). These results provide a strong evidence for the existence of a hierarchical architecture for confidence ratings. They also demonstrate the possibility of directly manipulating subjects' metacognitive efficiency and suggest specific ways of doing so.

Acknowledgments

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