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Pupil Dynamics Track Preparatory Control and Selective Learning in Decision Making

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Abstract

A unifying theory of phasic pupil responses suggests that pupil diameter reflects information gain following an observation. However, it remains unclear whether different types of information gain (Shannon surprise and belief updating) from different sources (control signals, decision-relevant stimuli, and decision-irrelevant stimuli) modulate pupil responses in similar or distinct ways. To address this, we developed a decision-making task that dissociates these information streams within a single trial. Analyzing pupillometry data from 30 participants, we identified two computational signatures. First, cue surprise modulated pupil responses before stimulus-driven effects emerged, indicating preparatory control. Second, learning-related information gain reliably modulated pupil responses after decisions and was selective for belief updates from decision-relevant stimuli, even though decision-irrelevant stimuli were also perceptually encoded. These findings refine the information-theoretic framework by revealing pupil modulation by proactive control and distinguishing automatic, surprise-related dilation from selective, learning-related dilation gated by decision relevance.