A theory of optimal feature selection during visual search

How does the human visual system select relevant locations and visual features (e.g., color, orientation) in order to quickly detect desired targets in distracting backgrounds? Although recent evidence suggests that humans can select relevant locations optimally, it is not yet known whether they can select visual features optimally. Several heuristics for feature selection have been proposed in the past, such as promoting the target's features in early visual areas like V1 and V2. But the correct choice of features depends on both the desired target as well as distractors in the background.

Here, we propose the first formal theory of how prior statistical knowledge of target and distractor features modulates the response gains of neurons encoding features, such that search speed is maximized. Through numerical simulations, we show that this theory successfully explains many reported behavioral and electrophysiological observations including top-down effects such as the role of priming, the role of uncertainty, target enhancement and distractor suppression, as well as bottom-up effects such as pop-out, the role of target-distractor discriminability, distractor heterogeneity, linear separabilty and others.

Contrary to most common heuristics which suggest promotion of target features in order to detect the target, the optimal theory makes surprising predictions that target features may sometimes be suppressed, or non-target features may be enhanced. We validate these counter-intuitive predictions through new psychophysics experiments. Four naive subjects performed a difficult search for a target bar tilted 55 degrees off vertical among distractor bars tilted 50 degrees. The gains thus set up were tested by randomly inserting probe trials, in which we briefly flashed (200ms) four items representing the distractor (50 degree), the target (55 degree), relevant as predicted by the theory (60 degree), and steep (80 degree) cues. As always, the task was to search for the target and report it. Although subjects searched for a 55 degree target, as predicted by the theory, there were significantly higher number of reports on the 60 degree item (paired t-test with $p < 0.05$). These results provide direct experimental evidence that humans may select visual features optimally.

This study bears implications for further research in understanding top-down attention during visual search. For instance, previous research in physiology focused on feature gain modulation during attention to a target feature, and largely ignored the role of the distracting background features. In contrast, our research suggests that the distractors play a crucial role in determining feature gains, and may even lead to suppression of target features or enhancement of non-target features. Investigating the modulatory effects during visual search call for new experiments in physiology, brain imaging and behavior.