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Relating color working memory and color perception

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Color is the most frequently studied feature in visual working memory (VWM). Oddly, much of this work de-emphasizes perception, instead making simplifying assumptions about the inputs served to memory. We question these assumptions in light of perception research, and we identify important points of contact between perception and working memory in the case of color. Better characterization of its perceptual inputs will be crucial for elucidating the structure and function of VWM.

Introduction

A typical research strategy in the cognitive sciences attempts to isolate individual mental systems. This approach has met a great deal of success. However, it also includes an underlying limitation: to the extent that we seek to explain the outputs of a system as a function of its inputs an inescapable requirement will be to accurately characterize those inputs.

Our present goal is to apply this lens to what is nominally the study of VWM. Because the lion's share of VWM research uses color as the memory feature, current theories depend a great deal on the nature of color working memory (CWM). Surprisingly, research on color perception is rarely invoked to characterize the inputs to CWM. Measuring and understanding perceptual interactions with working memory is ultimately a necessary step for characterizing the structure of VWM. Broadly, we suspect that few would disagree. Yet practically, these issues seem not to have permeated the design and interpretation of individual experiments. In what follows, we discuss three ways that the properties of color perception interact with working memory and the consequences of such interactions for theories of VWM. These include stimulus-specific properties in color perception, contextual processing in color perception, and feedback effects from the contents of working memory to online color perception.

Background: CWM and delayed estimation

Recent focus on color in the domain of VWM has been partly motivated by the wide adoption of the delayed estimation (DE) paradigm (Figure 1A) [1]. Although many of the points that follow extend to other paradigms, we will accordingly focus this discussion on DE. In a typical experiment, color samples are selected from a circular color ring that varies only in hue (Box 1). On each trial, between one and eight colored shapes appear for a study period. After a delay (100–1500 ms), participants are instructed to select, from the full ring of sample colors, the one that had appeared in a now-probed location. Because memory is imperfect, selected colors differ from those presented during the study period. This furnishes a continuous measure of response variability (Figure 1B) that can be quantified over trials and then analyzed with respect to hypotheses about VWM.

In particular, effects of memory load (the number of items in a sample) have become the fuel for ongoing debates concerning VWM limits [2]. We do not endorse any particular views in this regard. Instead, we discuss features of color perception that apply generally. Because all theories amount to causal explanations for the response variability observed as a function of experimental manipulation, it is important to identify potential sources of response variability that may originate outside of memory.

Stimulus-specific features of perception

Color perception and CWM research differ in their treatment of color as a stimulus. In the case of CWM, it is assumed that the response variability elicited by a memory target can be characterized independently of the target's specific color (e.g., [1–3] and see [4] for an in depth discussion; Figure 1C). Implicit in this assumption about memory is an additional assumption about perception: that variability in perception is also independent of the specific color perceived.

Color perception research, in contrast, typically measures responses to individual colors directly (usually operationalized as discrimination threshold). One germane reason is that accurately rendering color stimuli is technologically challenging. The light emitted from a monitor depends, in complex ways, on hardware and software [5]. Research in color perception standardly employs monitor calibration to faithfully render stimuli (Box 1). However, this practice is not employed in the DE literature [1–4].

Lack of calibration is not merely a theoretical concern. We have recently demonstrated that without appropriate calibration, rendered colors differ considerably from nominal ones, including in terms of luminance [4]. Because calibration has not been employed in the DE literature, it is very likely that the stimuli seen by observers differed from the stimuli they were intended to see.

Once stimuli are accurately rendered, further research should investigate whether response variability is uniform across stimuli. The color space often used in DE tasks (CIELAB; Box 1) aims for perceptual uniformity. Among

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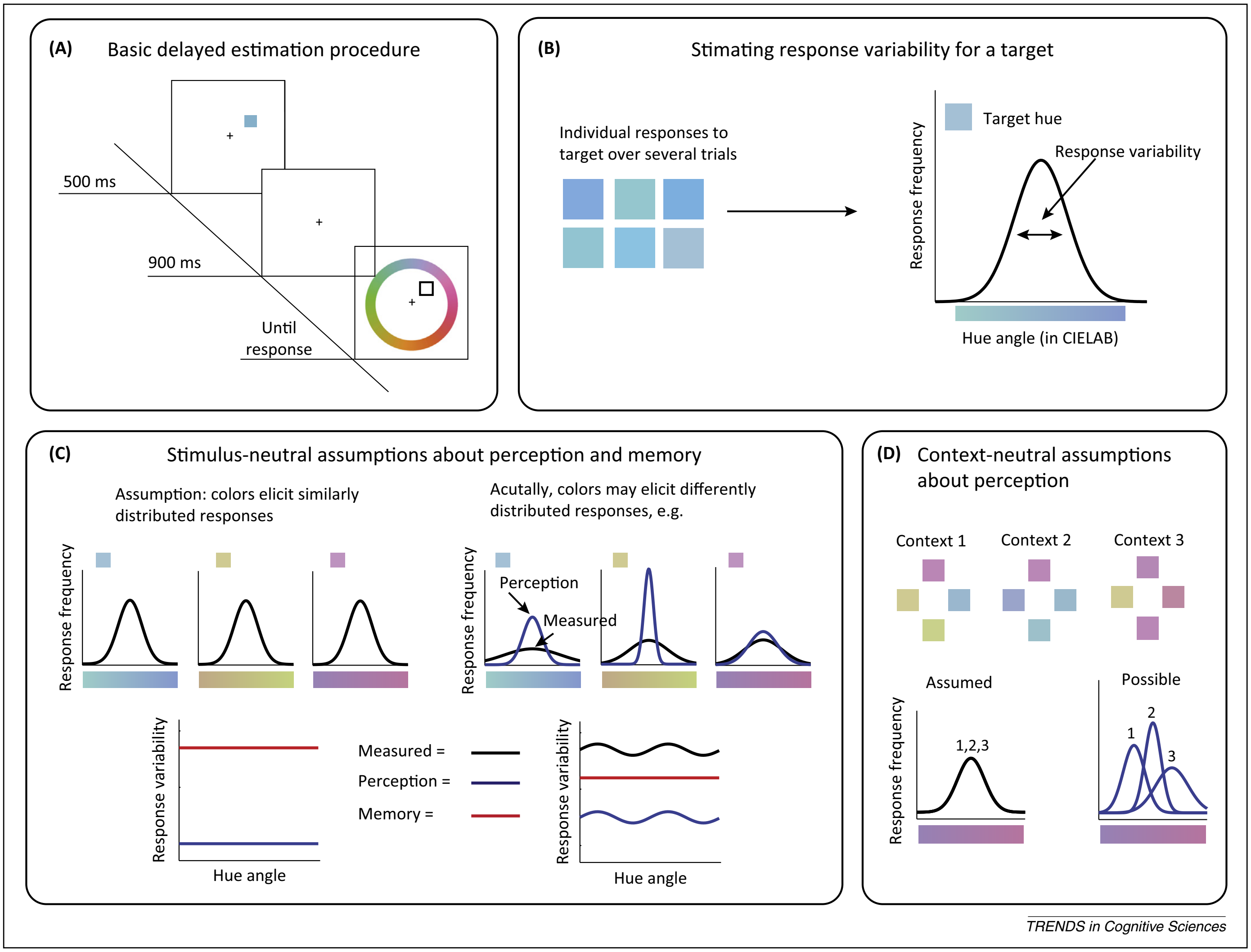

Figure 1. Delayed estimation methods and analytical assumptions. Panel **(A)** illustrates typical delayed estimation methods. In this example, one study square is displayed for 100 ms. After a 900-ms delay period, a colored ring of choice stimuli appears. The ring displays the larger set of sample stimuli in the experiment from which colors are drawn. Within the ring, a bold square outlines the probed location. In experiments with set size greater than one, the non-probed locations are outlined in normal-weight squares. The subject selects the remembered color with a mouse. Panel **(B)** illustrates the main analytical approach applied to these experiments. Over the course of an experiment, responses will vary relative to a target color. Summing the responses in terms of their distance from the target produces a histogram from which average response variability can be estimated. As shown in panel **(C)**, prevailing approaches assume that different individual colors will produce largely similar patterns of response (top left histograms). Thus, it is assumed that all measured response variability is due to memory (identical red and black lines in bottom left plot) relative to perception as a 0 point, and measured variability is constant across hue. As a result, researchers estimate response variability across all trials collectively. As we discuss, however, there are reasons to expect that perceptual variability is color-dependent (blue lines, right set of histograms). To isolate the contribution of memory (red line, bottom right panel) it is necessary to compare the measured variability in a delayed estimation (DE) task (black line), which combines perceptual and memory processes, to the perceptual variability alone (blue line). Panel **(D)** illustrates a second set of assumptions built into prevailing analyses, that responses elicited by a given color will be invariant as a function of its particular context. Three example contexts are shown. In each, the target stimulus (top center square) is identical, but the other study stimuli vary. Current models assume measured response variability is identical in all three contexts (left histogram). Again, there are reasons to question this assumption. Perceptual responses (and thus measured variability) may differ with context (blue lines show examples in right histogram).

other things, this means that two colors with some distance between them should be as discriminable as two other colors separated by the same distance. Although CIELAB represents an improvement over many other color spaces in this respect, it is imperfect [6]. Indeed, there are good reasons to suspect that a color space can never completely meet the goals of perceptual uniformity. For one, there are substantial differences in color perception between putatively color-normal observers. What counts as uniformity will therefore differ between observers. Moreover, one may expect color-specific response effects with large sets of colors because spanning linguistically or categorically separable regions is known to influence discrimination thresholds and response times [7]. These effects seem to originate in perception. In a straightforward perception experiment, we have found color-specific response effects that correlated strongly with those in a delayed (i.e., memory) version of the same experiment [4].

In practical terms, pervasive analytical approaches to DE assume that the geometry of the ring used to sample colors captures the geometry of perception, that is, that distances on the ring have proportion-preserving relationships to the perceptual appearance and discriminability of the stimuli. However, for the reasons outlined above, the assumption is unwarranted and most likely wrong.