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 deemphasizes 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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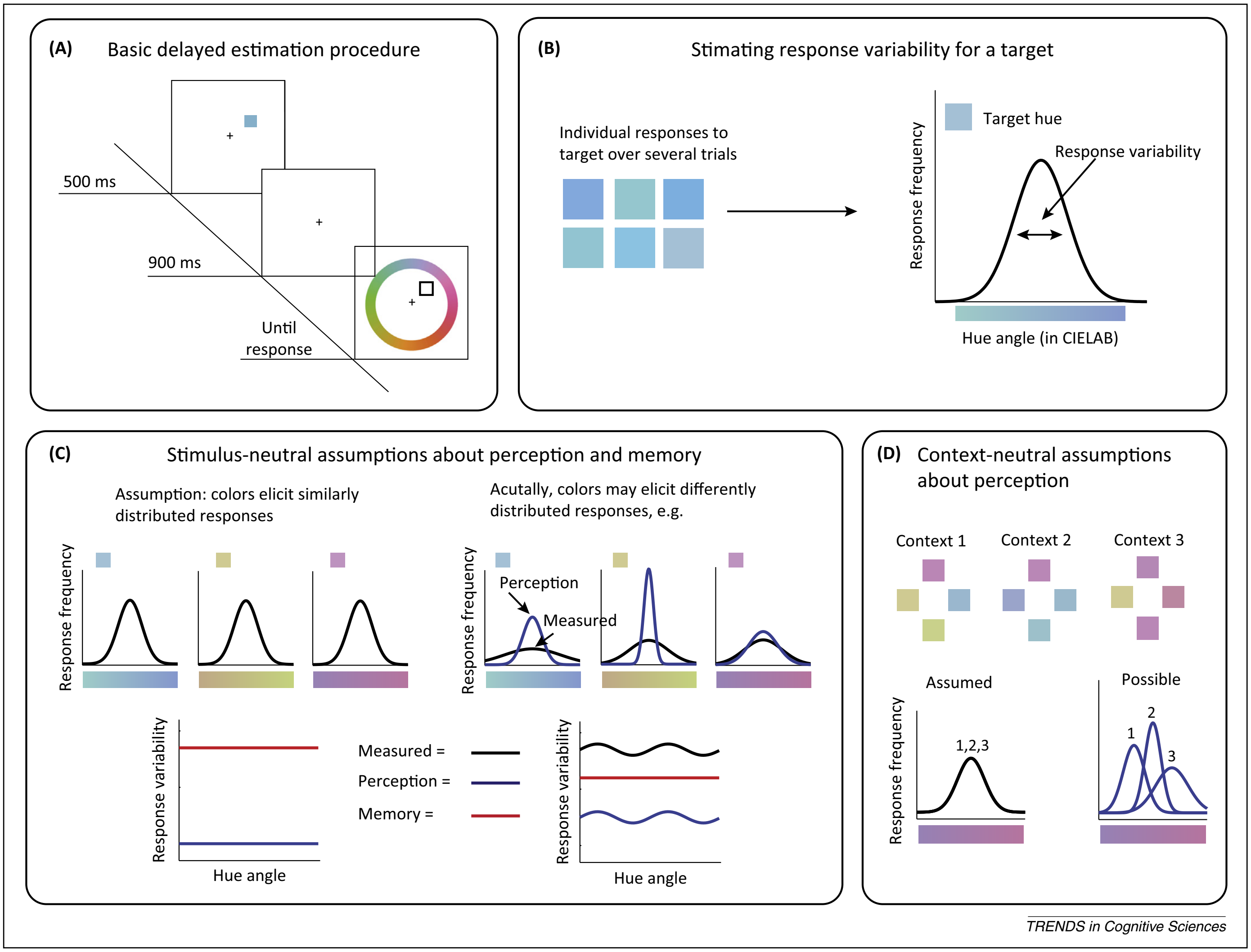

Figure 1. Delayed estimation methods and analytical assumptions. Panel **(A)** illustrates typical delayed estimation methods. In this example, one study square is displayed for 100 ms. After a 900-ms delay period, a colored ring of choice stimuli appears. The ring displays the larger set of sample stimuli 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.

Box 1. Glossary of color science terms and concepts

Calibration: in color perception experiments refers to the process of mapping graphics calls on a particular device to the physical outputs of the monitor used with that device. The light emitted from a monitor in response to different graphics calls varies with hardware and software. Calibration usually begins by using a radiometer to measure the light emitted from a monitor in response to a family of different graphics calls. See [5] for a detailed explanation of the processes involved in calibration. Different labs use different radiometers and software in the calibration procedure. The data obtained in the process of calibration also allow the user to determine specific colors that a device cannot render, and those that it can, called the gamut.

CIELAB: CIE L*a*b* (often written CIELAB) was developed as a perceptually uniform color space. It is a coordinate system for describing the discriminability of colors perceived by an observer, as opposed to the physical properties of a light stimulus (a wavelength-based space), or physiological responses (a physiologically-based space). It is achieved through non-linear transformations from the coordinates of a device-independent space, CIEXYZ. It is defined relative to a white point, which in color perception experiments is often either the illuminant or the background color of the monitor. Note that the International Color Consortium (ICC) standard white point provided within many software routines is an approximation of one particular illuminant. L* is a dimension of lightness (black to white), and a* and b* are opponent color dimensions roughly corresponding to green/magenta and blue/yellow. If L* is held constant, the 2D plane through the space can be described in terms of polar coordinates, with angle representing hue, and distance from the origin representing saturation (chroma).

Color constancy: refers to stable color appearance of an object across changes in that object's context, such as background and illumination. It is unlikely that the human visual system achieves perfect constancy. A review of constancy research can be found in [8].

As a consequence, it is problematic to use response variability across stimuli as a proxy for representational precision, currently a crucial step in theorizing. In particular, models of working memory typically characterize representational precision with a single, color-agnostic parameter (e.g., [1–4]). Conclusions about the structure of memory are then drawn on the basis of how experimental conditions such as memory load influence that parameter, under the hypothesis that representational precision is constrained by the allocation of limited memory resources. When we previously fit the parameter individually to uncalibrated colors, rather than using one parameter for all colors, we found that the effects of color on the parameter were in some cases two to three times larger than the effects of memory load using standard, stimulus-neutral analyses. The theory that limited resources determine representational precision thus needs a mechanism for explaining stable between-color differences that are bigger than effects putatively caused by a straightforward division of resources (in the case of memory load).

Similarly, recent work has suggested a re-conception of VWM storage as inconsistently allocating resources from moment to moment. The observation that motivates this theory is the discovery of stochastic response variability on a trial-by-trial basis [3]. However, in an important sense, the relevant experiments have a stochastic trial-by-trial variable by design because individual trials comprise different sets of individual colors.

By assuming simplified perceptual inputs to the system, many models of CWM may be modeling the wrong things, namely, response variability that originates in perception as opposed to memory and which may arise through interactions with color categories and labels, as opposed to stimulus-neutral sources of noise.

Context-specific features of perception

A main focus of interest in the study of VWM is storage capacity, usually studied by manipulating memory load. Increasing the number of items in a display quickly affects response variability [1–3]. How readily should changes in response variability be attributed to the nature of storage?

Because the perceived color of a stimulus depends in complex ways on elements of scene composition, increasing memory load can have a collateral impact with origins in perception. Contextual effects in color perception have been widely studied under the rubric of simultaneous contrast and color constancy [8]. Although the mechanisms underlying color perception in complex scenes are not entirely understood, one point of consensus is relevant to CWM.

Specifically, the color characteristics of items added to a scene can alter the perceived color of a target [8,9]. These effects may arise because color perception mechanisms reference objects to one another in light of scene-general properties such as background and illuminant. Thus, the method used to increase memory load may also change the initial perception of those items, confounding memory effects with perceptual effects (Figure 1D). It would be convenient if we could assume that a given stimulus is always perceived in the same way – regardless of its particular context – and therefore, that any output distortion in a working memory task is caused by properties of memory. However, an overwhelming amount of color perception research suggests that two identical stimuli (of the kind used in VWM experiments) can evoke very different perceptual responses – and therefore, very different inputs to working memory – when they are embedded in different contexts [8,9]. Consequently, manipulations of memory load are always manipulations of context, and it should be expected that they modulate the perceptual inputs to memory.

To our knowledge, no previous work has investigated working memory in exactly these terms. However, two recent studies have shown how responses to a memory target can be influenced by the particular qualities of temporally or spatially nearby items. In the first study, participants remembered the luminance of either one or two objects. When the items' hues differed categorically, memory for luminance was unimpaired relative to memory for a single item (but impaired when they were the same hue) [10]. Memory costs for two compared to one are a critical prediction of what are known as continuous resources theories of WM limits, but in this study, they were altogether absent for scenes including two objects that differed in hue. The second study found that memory for a single item is influenced by a colored mask following presentation, but only by masks within a circumscribed color distance from the memory target [11]. In this case, the relational interaction was temporal (as opposed to spatially simultaneous). Nonetheless, it suggests that specific colors can influence the ways other specific colors are remembered, a point that is consistent with work in a variety of domains beyond color [12].

Influences of working memory on color perception

Just as objects within a scene mutually influence perception of one another, the current contents of working memory influence the perception of objects in view. Interpreting the present by reference to the recent past is one way to moderate the basic inverse challenge of perception. Practically and theoretically, this means that perception and working memory should be difficult to isolate, an intuition confirmed by recent empirical evidence. For example, individual differences in color constancy correlate with individual differences in working memory performance [13], and there are also documented interactions between working memory and context-dependent color perception [14]. These results belie typical conceptions of constancy computations as 'low-level', and moreover, they are consistent with recent studies that identify a role for early visual areas in working memory maintenance [15].

Concluding remarks

Perception and working memory may be conceptually distinct – systems that could operate independently, with one merely feeding into the other. However, as implemented in humans, at least in the case of vision, and with respect to color in particular, they appear to be cooperative and considerably inextricable. As a result, understanding how and why VWM selects, compresses, and distorts the inputs served by perception is unattainable without characterizing those inputs. What we call 'perception' and 'working memory,' at least in the case of color, are mechanisms that appear to share a central concern, representing (as usefully as possible) the material properties of the surfaces that we encounter.

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