*PI: Jonathan Flombaum*

**Psychology Education Title**

**The Precision of Visual Working Memory with Delayed Estimation**

**Overview:**

Human memory is limited. Throughout most of its history, experimental psychology has focused on investigating the discrete, quantitative limits of memory — how many individual pieces of information a person can remember. Recently, experimental psychologists have also become interested in more qualitative limits —how *precisely* is information stored?

The concept of memory precision can be at once both intuitive and elusive. It is intuitive, for example, to think that a person will remember precisely how their mother sounds, making it possible to recognize one’s mother immediately over the phone or in a crowd. But how can one quantify the precision of such a memory, exactly how similar it is to the voice itself?

To study the precision of memory, and working memory in particular, experimental psychologists have devised a paradigm known as delayed estimation. It has been used most often, thus far, to study the precision of visual memories, especially memory for color. This video demonstrates standard procedures for investigating the precision of color working memory using delayed estimation.

**Procedure**

1. **Stimulus design**
   1. The key to any color working memory experiment is to choose a large set of individual colors that can serve as stimuli from trial to trial. Importantly, the colors need to have the same luminance (intensity of light) and the same contrast relative to the background, in order to prevent any one color from being naturally more memorable than any other. Most experiments include 180 individual colors, each with the same luminance, but varying in hue (Figure 1).
2. **Procedure**

**2.1.** Each experimental trial includes three parts (**Figure 2**):

A. The sample phase: One of the 180 colors is selected randomly, and presented in the display within a small square for 100 ms.

B. The delay: The sample disappears, and the participant faces a blank display for 900 ms.

C. The test: An empty square appears, along with the full color ring. The participant’s task is to recall the color seen during the sample phase (part A), and to click (with the mouse) that color on the ring.

1. **Analysis**

**3.1** To understand the analysis of delayed estimation data, consider a hypothetical scenario in which the same color is the sample on many trials (Figure 3). The participant will not always respond with exactly that color. They also won’t respond with ones that are very different, so the expectation is that the exactly correct color is selected most frequently. Colors very similar to it should be selected less often, but still frequently. And very different colors should be selected almost never. This kind of pattern can be described mathematically in terms of a normal distribution — a bell curve. The correct answer should be the average response over many trials, but owing to imprecision in memory, there should also be some spread. Quantifying the spread amounts to quantifying the precision of color working memory. Here is how it is done (figure 3).

**3.2** The raw data on each trial are a response color and the true target color. That means that the accuracy of a response on each trial can be quantified in terms of the angular difference between the right answer and the given answer. Recall that the colors —including the target and any response— make up a ring, occupying a total of 360 degrees. For each trial, compute the angular response error. When the answer given is exactly right, the angular error will be zero, and the most it can ever be is 358 degrees.

**3.3** Because the colors all have equal luminance and contrast, responses can be collapsed across color targets —analyzed just like they would be in the hypothetical case of a single color repeated many times. In other words, angular error amounts to a color-agnostic way of characterizing the accuracy of each response, and angular errors can be averaged across all trials under the assumption that there is no reason for any one color to produce average angular errors larger than any other.

**3.4** In this way, the responses across all trials can be used to generate a distribution of the frequency of different angular errors. Such a distribution is shown in **Figure 4**. Note that the mean of the distribution is zero and that it is normally distributed.

**3.5** From the distribution of angular errors, the precision of color working memory can be computed. Specifically, the standard deviation of the distribution is the most often used measure to describe the spread of responses. A large standard deviation means that the distribution has a lot of spread and variability, a reflection of relatively imprecise responses. A small standard deviation reflects a tight distribution, and precise memory. In this way large numbers reflect imprecision and small numbers reflect precision, so scientists often use the inverse of the standard deviation (one divided by the standard deviation) to quantify precision. Now large numbers designate precise memories and small numbers designate imprecise memories.

**Representative Result**

A common reason to investigate the precision of color working memory with delayed estimation is in order to understand the relationship between discrete and continuous aspects of memory. Does remembering more individual objects produce less precise memories? The answer seems to be yes. A typical experiment will involve one or more color squares on each trial, with the participant instructed to remember all, but only tested one after the delay (**Figure 5**).

When this experiment is conducted, researchers typically compute memory precision just as described, but independently for memory load, which refers to the number of color squares in a trial.

With higher memory loads, precision tends to decline (**Figure 6)**, suggesting a tradeoff between how many things a person can store in memory and how precisely they can store those things.

**Applications**

Delayed estimation is a relatively new paradigm in experimental psychology, though it has become rapidly influential. In addition to investigating tradeoffs between memory capacity and precision, it can be used to compare the precision of memory systems, such as color working memory compared to color long term memory, and also to compare precision across individuals. For example, do interior decorators or painters tend to have more precise memory of color, than say lawyers or doctors?

**Legend:  
Figure 1 –** A color ring including 180 individual colors. The ring is shown rendered in CIELAB space. All samples have the same L\* coordinate value, roughly meaning that they have the same luminance. The center point of the ring (shown accurately in grey) is an achromatic point, with the same luminance as the sample colors, but not chromatic value (i.e. with a\* and b\* coordinates equal to zero). The 180 individual color samples vary in terms of a\* and b\* values, specifying their proportional mixtures of blue/yellow and magenta/green to produce each individual color.

**Figure 2 –** Delayed estimation procedure. In each trial, one of the 180 individual colors (‘the sample’) is shown for 100 ms, the display becomes blank for 900 ms, and then the participant must report the remembered sample color via mouse click on the color ring.

**Figure 3 – Hypothetical analysis assuming the same color feature on each trial.** Supposing the blue labeled ‘actual target color’ were the memory target over many trials, one would expect that color to obtain the most responses (i.e. the highest response frequency), with roughly a normal distribution for nearby blues. In other words, one should expect normally distributed responses with the actual target as the mean of the distribution. The variability in the distribution can supply a measure of memory precision.

**Figure 4 —** Frequency of angular errors, collapsed across all trials, over the course of an experiment. Errors should form a normal distribution, centered on zero —indicating the correct response as the average answer. The variability of the distribution, specifically, the standard deviation can be used to estimate memory precision.

**Figure 5 –** Delayed estimation with four sample items. The participant is instructed to remember all four colors, but only one item is probed at test.

**Figure 6 –** Memory precision as a function of memory load, the number of color samples to remember in a given trial. Note that the unit of precision is inverse degrees, (1/ °), since the unit of angular response error and its standard deviation is degrees.