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Detection of small orientation changes and the precision of visual working memory

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ABSTRACT

We investigated the precision of orientation representations with two tasks, change detection and recall. Previously change detection has been measured only with relatively large orientation changes compared to psychophysical thresholds. In the first experiment, we measured the observers' ability (d') to detect small changes in orientation (5–30°) with 1–4 Gabor items. With one item even a 10° change was well detected (average $d' = 2.5$). As the amount of change increased to 30°, the d' increased to 5.2. When the number of items was increased, the d's gradually decreased. In the second experiment, we used a recall task and the observers adjusted the orientation of a probe Gabor to match the orientation of a Gabor held in the memory. The standard deviation (s.d.) of errors was calculated from the Gaussian distribution fitted to the data. As the number of items increased from 1 to 6, the s.d. increased from 8.6° to 19.6°. Even with six items, the observers did not make any random adjustments. The results show a square root relation between the d'/s.d. and the number of items. The d' in change detection is directly proportional to the square root of $(1/n)$ and the orientation change. The increase of the s.d. in recall task is inversely proportional to square root of $(1/n)$. The results suggest that limited resources and precision of representations, without additional assumptions, determine the memory performance.

1. Introduction

Humans are highly accurate in several visual and spatial discrimination tasks that do not require memory. The discrimination threshold for spatial displacement is below the resolution of the cone spacing in the retina (e.g., Findlay, 1973; Westheimer & McKee, 1977), for spatial frequency the discrimination threshold is only a few percent (e.g., Hirsch & Hylton, 1982; Wilson & Gelb, 1984), and for orientation the discrimination threshold is less than 0.5° (e.g., Vogels & Orban, 1986; Westheimer, 1998). With a short interval (<1000 ms) between the stimulus pair to be discriminated, and hence due to memory representations required in the task, the orientation discrimination thresholds increase to a few degrees depending on the stimulus length and stimulus type, and further increases as the inter-stimulus-interval extends (Henrie & Shapley, 2001; Vogels & Orban, 1986). For a single item the fidelity of orientation diminishes somewhat faster than other basic visual features, such as spatial frequency and contrast (Magnussen, 2000; Pasternak & Greenlee, 2005).

During the recent years, the interest in memory research has shifted from estimating memory capacity (e.g., Luck & Vogel, 1997) to the content of the representations (for recent review, see Brady, Konkle, & Alvarez, 2011), and precision of memory representations has been investigated in several studies (e.g., Zhang & Luck, 2008). When more than one item is to be remembered, the precision of memory decreases. The spatial frequency discrimination thresholds for two items are more than 4-fold compared to a single item threshold (Greenlee & Magnussen, 1998) and shape discrimination thresholds increase linearly as a function of set size (Salmela, Lähde, & Saarinen, 2012). In orientation discrimination, the slope of the psychometric function decreases immediately as the number of items increases (Bays & Husain, 2008; Jiang, Shim, & Makovski, 2008; Palmer, 1990), and with a subjective adjustment task, the standard deviation of the errors of orientation adjustments increases as the number of items to be remembered increases (Wilken & Ma, 2004). A similar type of decrease in precision has also been shown for spatial frequency (Wilken & Ma, 2004) and for color (Bays, Catalao, & Husain, 2009; Wilken & Ma, 2004). All of these studies show a clear tradeoff between memory capacity and the precision of representations. This has been attributed to the increasing internal noise (Wilken & Ma, 2004) or the dynamic allocation of resources (Bays & Husain, 2008).

In previous psychophysical studies the discrimination and memory precision for the orientation of a single item has been studied extensively (Magnussen, Idas, & Myhre, 1998; Vogels & Orban, 1986). However, the precision for the orientation of multiple items have been investigated only recently (but see Palmer, 1990) and the estimates of the precision of orientation representations (Bays & Husain, 2008; Jiang, Shim, & Makovski, 2008; Wilken & Ma, 2004) are much lower than the psychophysical thresholds

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would predict. Further, in previous change detection studies (Luck & Vogel, 1997; Wilken & Ma, 2004), relatively large orientation changes (22.5–45°) compared to discrimination threshold (<5°) have been used. If memory precision depends on the set size, then the amount of change that can be reliably detected should also depend on the number of items. We investigated the changes in memory precision with small number of items, especially how the number of items (1–4) and the amount of orientation change (5–30°) affect the precision of memory representations. The delayed detection of small change in Gabor orientation (5–30°) was measured with a same-different task in a change detection setup (Fig. 1A). We quantify the observers' performance and the precision of memory with the *d*′. The models based on signal detection theory (Bays & Husain, 2008; Wilken & Ma, 2004) suggest that the precision should be proportional to the amount of orientation change. Thus, we expect that the observers' performance with different amount of orientation change should be identical in shape, but in different scale. Due to the limited resources, the precision should gradually decrease as the number of items increase and be proportional to $1/n$ (Bays & Husain, 2008; Wilken & Ma, 2004).

The change detection task is quite challenging and observers performance is typically lower than in other perceptual tasks, such as yes/no (Macmillan & Creelman, 2005), and thus the change detection task could underestimate the memory precision. To get another estimate for memory precision for orientation, we conducted a second experiment and measured distribution of adjustment errors in the subjective recall task (Fig. 1B). The results were analyzed with Zhang and Luck's (2008) maximum likelihood model to separate the precision of memory representations from random responses (due to memory failure). We expect that the precision (s.d. of the error distribution) should decrease, similarly to the first experiment, in proportion to $1/n$ (Bays & Husain, 2008; Wilken & Ma, 2004). Further, the slot model (Zhang & Luck, 2008) suggests also an asymptotic precision level as the number of items exceeds the number of slots. In both experiments, the stimulus duration (300 ms/item) was kept long to ensure enough encoding time and to keep random responses minimal (Bays, Catalao, & Husain, 2009). To emphasize the role of working memory, the inter-stimulus-interval was 1500 ms.

2. Methods

2.1. Equipment, stimulus and observers

The experiments were conducted using a Matlab (MathWorks Inc., Natick, MA) and ViSaGe stimulus generator (Cambridge Research Systems, Cambridge, UK). The display was a calibrated and linearized Mitsubishi Diamond Pro 2070SB monitor (display size 11.2° × 8.4°; pixel size 0.84 arcmin; refresh rate 100 Hz; mean luminance 44.5 cd/m^2). The viewing distance (2.0 m) was held constant with a chin-rest. The experiments were conducted under dim room illumination. Six observers with normal or corrected-to-normal vision participated in the two experiments (one observer participated only in the first experiment). Four observers (IK, MK, and the authors JS and VS) were very experienced in psychophysical

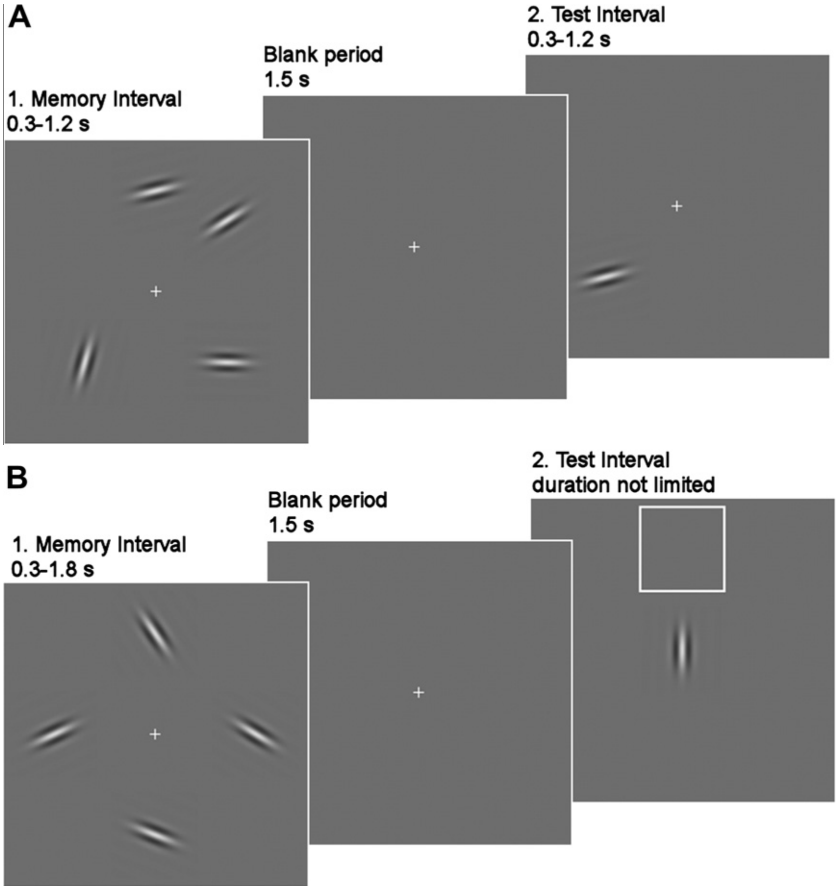

Fig. 1. Experimental setups. (A) Two-interval change detection. Each experimental trial consisted of two intervals: a memory interval and a test interval separated by a blank 1.5 s retention period. In half of the trials the single item in the test interval was rotated either clockwise or counter-clockwise compared to the memory interval, and the observers' task was to detect the orientation change with a same-different task. In the figure, the target Gabor has been rotated 60° clockwise in the test interval. (B) Recall experiment. The memory interval and the blank period were identical to the change detection experiment. In the test interval, observers adjusted the central Gabor to match the orientation of the cued (a white box) Gabor.