Research Report

HIGH-FIDELITY PERCEPTUAL LONG-TERM MEMORY REVISITED—AND CONFIRMED

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Abstract—*Experiments on short-term perceptual memory for elemental visual attributes, such as contrast, motion, orientation, and spatial frequency, have relied on a delayed discrimination technique in which the subject compares two stimuli presented at different points in time and memory is indexed by discrimination thresholds measured for the different time intervals between reference and test. In a variant of this procedure, used in experiments on long-term memory, the presentation of a single reference is followed by a memory test that combines two-alternative forced-choice decisions with the method of constant stimuli. With this procedure, it is impossible to distinguish the effects of criterion-setting processes and memory on performance, but this confound can be eliminated by testing many subjects and having each subject make a single decision. The resulting "group thresholds" are stable across time intervals of 24 hr, confirming previous findings of high-fidelity storage in the long-term memory range.*

The concept of perceptual memory or sensory memory refers to the storage of elementary attributes or dimensions of sensory stimuli (Laming & Scheiwiller, 1985). Recent studies of perceptual memory in the visual modality have focused on stimulus attributes analyzed by neurons in the primary visual cortex (V1)—spatial frequency, orientation, motion, and contrast (DeValois & DeValois, 1990; Livingstone & Hubel, 1988)—on the idea that if these attributes are important in on-line analysis of visual images, they may also be important in storing images (Magnussen, 2000; Magnussen & Greenlee, 1999). The experiments have been modeled on a delayed discrimination paradigm in which a test stimulus is compared with the memory representation of a previously presented reference stimulus (e.g., Blake, Cepeda, & Hiris, 1997; Lee & Harris, 1996; Magnussen, Greenlee, Asplund, & Dyrnes, 1991; Magnussen, Idås, & Holst Myhre, 1998; Regan, 1985), and memory decay is indexed by changes in discrimination thresholds or some equivalent measure as the interstimulus interval is increased. The general finding of this research has been that information about elementary stimulus dimensions is extremely well retained during short-term and quasi-short-term memory intervals (Magnussen & Greenlee, 1999).

Magnussen and Dyrnes (1994) extended the retention interval in perceptual memory research into the long-term memory range. In this experiment, groups of subjects were initially shown a grating with a spatial frequency of 2.5, 5, or 10 cycles/deg for 10 s and then tested either immediately or after an interval of 30 min, 5 hr, or 50 hr. In the test session, they were shown a series of gratings covering a range of spatial frequencies, randomly presented according to the method of constant stimuli. The subjects decided whether each test grating had a higher or lower spatial frequency than the previously viewed reference grating. The resulting psychometric functions were overlapping and had similar slopes for all retention intervals, with discrimination thresholds (Weber fractions) of 0.06 to 0.09, indicating almost perfect retention of spatial frequencies across intervals of 2 days.

In a more recent article, Lages and Treisman (1998) questioned whether any conclusions regarding perceptual memory can be drawn from delayed discrimination experiments of the sort reported by Magnussen and Dyrnes (1994). They offered an alternative account of the results in terms of criterion-setting theory, according to which the subject's higher/lower decision on a given trial is based on a representation of the whole range of recently presented test spatial frequencies rather than on a comparison of each test frequency with a representation of the single reference frequency. Lages and Treisman conducted two experiments with the method of constant stimuli; criterion-setting and perceptual memory theories predicted different outcomes, and the obtained results were consistent with the former. First, they found that for a fixed reference grating presented once, the psychometric functions were horizontally displaced when the range of test stimuli was shifted upward or downward, but did not change in slope or symmetry. Second, they found that the psychometric functions obtained in the absence of a reference grating, by simply running the test series and instructing the subjects to infer the midpoint, were identical to the psychometric functions obtained by presenting a reference grating before running the test series. In both experiments, Weber fractions were between 0.08 and 0.09, only slightly higher than the values reported by Magnussen and Dyrnes. Other psychophysical experiments have shown that such internal standards can be established after as few as 10 to 20 trials (Morgan, Watamaniuk, & McKee, 2000; Vogels & Orban, 1986). These findings raise the possibility that the results of Magnussen and Dyrnes were contaminated by the process of criterion setting, and consequently did not reflect perceptual long-term memory but rather reflected a different sort of short-term storage (Lages & Treisman, 1998), or a mixture of influences by long-term memory and criterion-setting processes.

As a first step in separating genuine perceptual long-term memory from confounding criterion-setting processes, we conducted a simple experiment, introducing the concept of "group thresholds": For criterion-setting processes to work in determining the psychometric functions in temporal two-alternative forced choice with the method of constant stimuli, each subject must be tested with a range of test spatial frequencies, with several trials per spatial frequency. Magnussen and Dyrnes (1994) sought to minimize the influence of such processes by running few trials per subject, and we maximized this strategy of trading trials for subjects in a single-trial experiment in which many subjects each made one independent judgment about the relative spatial frequency of reference and test gratings.

METHOD

Sinusoidal gratings with a contrast of approximately 30% were presented in a circular window on a Panasonic 56 monitor (resolution

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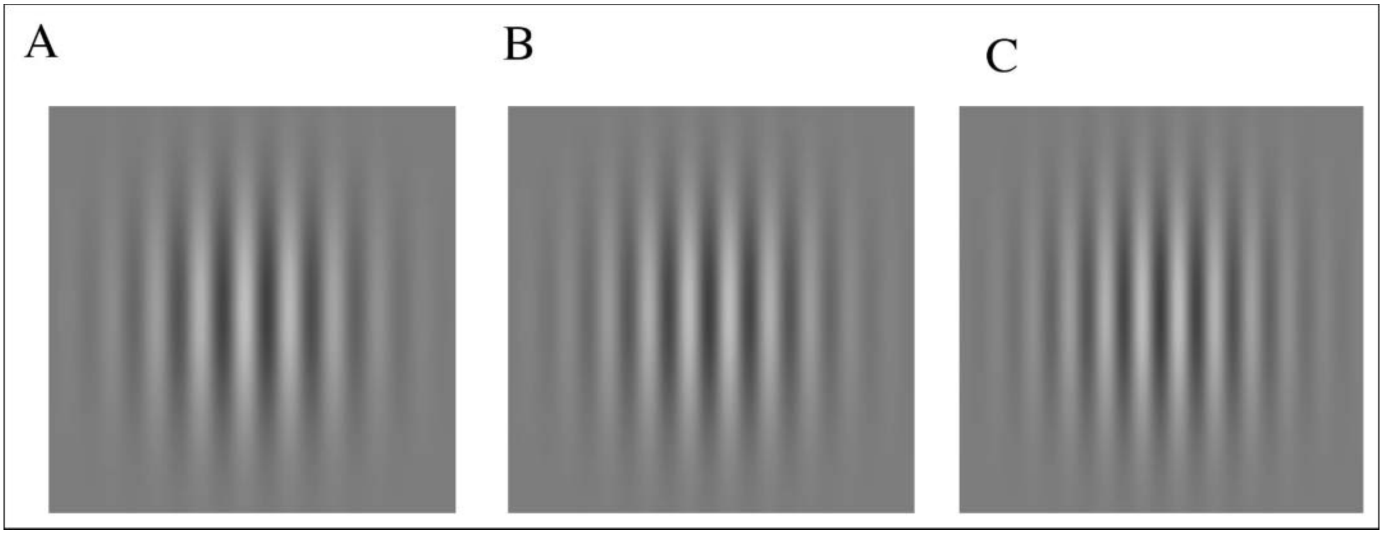

Fig. 1. Reference (b) and test (a, c) stimuli used to demonstrate long-term memory of spatial frequency. In the example shown here, the spatial frequencies of the test stimuli in (a) and (c) differ from the spatial frequency of the reference stimulus by −10% and +10%, respectively.

of 800 × 600 pixels). The grating field subtended 15° of visual angle, the reference spatial frequency was 3 cycles/deg, and test spatial frequencies deviated ±10 or 20% from the reference frequency. Figure 1 shows a scaled-down representation of the stimuli. Subjects were comfortably seated, supported by a chin and forehead rest, and viewed the stimuli at a distance of 57 cm. Presentation time was 5.0 s for both reference and test stimuli. The short presentation times and the spatial extent of the stimulus gratings, yielding a total of 45 black stripes in the pattern at a spatial frequency of 3 cycles/deg, precluded categorical or verbal coding of the relevant information (i.e., counting stripes) to assist memory.

Subjects were tested individually, with study and test conditions separated by an interval of 24 hr, keeping time of day a constant factor. Upon arriving in the laboratory on the 1st day, subjects were informed that they were to participate in a memory experiment, and the nature of the experimental task was explained. The task was illustrated by showing two gratings whose spatial frequencies differed by a factor of 3, and subjects were requested to judge which of the gratings had the thinner bars. They were further told that in the experiment proper the difference between the gratings would be much smaller, and that they might have to guess. After a brief pause, they were then presented with the reference grating. Returning to the laboratory the next day, they were presented with a single test grating and asked to decide whether it had a higher or lower spatial frequency (thinner or fatter bars) than the reference grating.

To have a baseline for group thresholds—as compared with individual thresholds under short-term memory conditions, in which perfect retention of spatial frequency is a well-established fact—we ran control conditions in which subjects were presented with reference and test gratings whose spatial frequencies differed randomly by ±10 or 20%. The interstimulus interval in this condition was 5 s. A total of 166 subjects, recruited from the student population at the University of Tromsø, Tromsø, Norway, were randomly assigned to the four test spatial frequencies (deviation of +10, −10, +20, or −20%) at the two retention intervals (short-term or long-term memory).

RESULTS AND DISCUSSION

The results are shown in Figure 2, which plots the proportion of subjects responding “higher” as a function of the relative spatial frequency of the test grating; results are fitted with Weibull functions (Lages & Treisman, 1998; Magnussen & Dyrnes, 1994). The curves for short- and long-term memory are almost overlapping. The spatial frequency discrimination threshold is defined as half the spatial frequency difference between the 25% and 75% intersection points, and the group thresholds calculated from the functions were only slightly higher for the 24-hr test-reference separation (0.105) than for the baseline condition (0.095). To test whether the distributions were different, we applied chi-square tests to delta values obtained pooling correct and incorrect responses for trials with ±10% deviation and trials with ±20% deviation, respectively. This procedure gave chi-square values of 0.58 for the 10% conditions and 0.53 for the 20% conditions; a statistical significance level of .05 would require a chi-square value of 7.81 (assuming 3 degrees of freedom). Thus, the small difference between the psychometric functions is not statistically significant.

Not surprisingly, these group thresholds of spatial frequency discrimination, which add interindividual variation to intraindividual variation, are higher than the thresholds reported in most delayed discrimination experiments with single subjects (Bennett & Cortese, 1996; Magnussen & Greenlee, 1999). However, delayed discrimination thresholds depend on a number of experimental factors, and the present values are well within the range of values reported in other experiments based on extensive single-subject testing (Magnussen et al., 1998). The spatial frequencies of the gratings in Figures 1a and 1c differ from the spatial frequency of the grating in Figure 1b by −10% and +10%, respectively, corresponding to the discrimination thresholds obtained by single-trial group testing.

Magnussen and Greenlee (1999) proposed that elementary attributes of the visual stimulus are stored in a perceptual memory mechanism that is connected to the perceptual representation system, PRS (Schacter, Wagner, & Bruckner, 2000; Tulving & Schacter, 1990). The PRS is believed to consist of a number of subsystems, one of which is a structural description system that computes information about the global form and

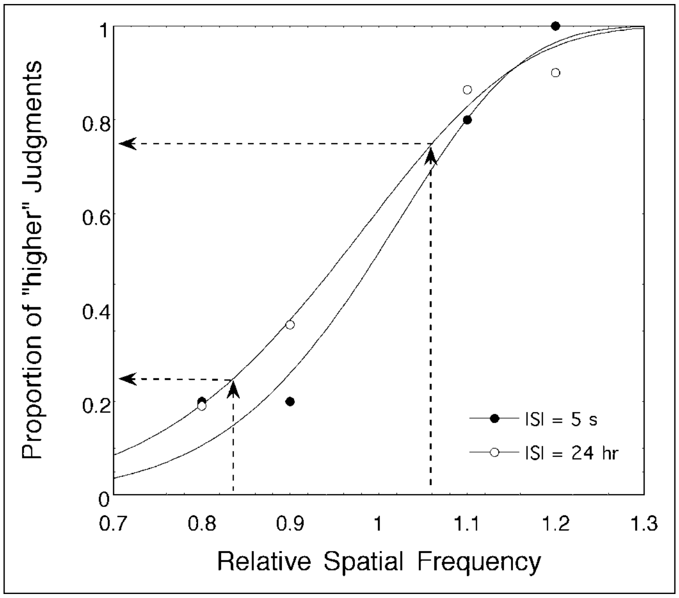

Fig. 2. Proportion of subjects guessing that the test grating had a higher spatial frequency than the reference grating as a function of the relative spatial frequency of the test grating, for interstimulus intervals (ISIs) of 5 s and 24 hr. Each point represents 20 to 22 subjects. Data points for each ISI have been fitted with a Weibull function. The dashed lines indicate the .25 and .75 intersections on the psychometric functions; the discrimination threshold for each function equals half the spatial frequency distance between these intersections.

structure of visual objects. The evidence suggests that the perceptual memory mechanism probed in what we, as a shorthand expression, have termed V1-attribute experiments is in fact located beyond V1 (Magnussen, 2000; Magnussen & Greenlee, 1999). Briefly, the argument rests on the discrepancy between the fact that memory-masking and dual-judgment experiments (Bennett & Cortese, 1996; Magnussen, Greenlee, & Thomas, 1996; Magnussen et al., 1991; Thomas, Magnussen, & Greenlee, 2000) show within- but not between-domain interactions and the fact that single V1 neurons are tuned to multiple dimensions (DeValois & DeValois, 1990; Livingstone & Hubel, 1988). On the other hand, given that judgments of V1 attributes such as spatial frequency and orientation are not subject to perceptual priming (Magnussen et al., 1998; see also Cave, Bost, & Cobb, 1996), the mechanism must be located prior to the structural description system of the PRS (Schacter, 1994).

What is the function of such high-fidelity storage of spatial frequency information? The memory mechanism probed in the present experiment may have a limited operating range and assist in the formation of more permanent high-precision representations of objects and meaningful patterns (Magnussen, 2000). The consolidation of memory representations for permanent storage can take days or even weeks (Squire & Kandel, 1999).

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