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Limited-capacity Mechanisms of Visual Discrimination

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Discrimination thresholds of spatial frequency and choice reaction times (RT) were measured in three subjects who performed a dual-judgment delayed discrimination task. Two reference gratings were presented side-by-side with a 0–800 msec stimulus onset asynchrony (SOA), which were followed after a 5-sec retention interval by two test gratings. Subjects judged which component changed and which interval had the higher spatial frequency (SF). Thresholds in the dual-judgment task were four to six times higher than thresholds in single-judgment tasks. The SOA had only a moderate effect on discrimination thresholds, whereas the difference between the spatial frequencies of the two components had a highly significant effect. The discrimination thresholds increase with increasing spatial frequency difference for the lower SF component, while they decrease for the higher SF component. An analysis of the distribution of possible error types indicated that all subjects tended to respond more frequently that the higher SF component changed. This tendency led to more errors on trials where the low SF component changed. A *post-hoc* analysis revealed, in two of the three subjects, a significant correlation between $\Delta f/f$ and RT such that higher $\Delta f/f$ values were associated with lower RTs and vice versa. © 1998 Elsevier Science Ltd. All rights reserved.

Divided attention Perceptual discrimination Short-term memory Spatial frequency

INTRODUCTION

It is now generally acknowledged that the processes of perception, attention and memory do not form global, unitary cognitive systems but are organized in a modular fashion with multiple, parallel systems devoted to specialized information processing and control tasks (Allport, 1989; Posner & Petersen, 1990; Tulving, 1991; Cowey, 1994; LaBerge, 1995). In vision, the principle of modular organization is encountered at several levels of functional analysis (Lennie, *et al.*, 1990; Cowey, 1994). The on- and off-channels of the retina and visual pathway are conceived as independent, antagonistic functional systems for signalling brightness versus darkness (Fiorentini, *et al.*, 1990), there is evidence for separate neural subsystems for the analysis of stimulus dimensions such as color, motion and form in the early stages of cortical processing (Livingstone & Hubel, 1987; Corbetta, *et al.*, 1991; Zeki, 1993), and there is a major division between cortical processing streams to parietal and temporal areas which might be implicated in the "what" and "where" questions of visual perception (Van Essen, *et al.*, 1991; Van Essen & DeYoe, 1995).

Human memory likewise consists of several major independent systems (Squire, 1987; Tulving, 1991; Tulving, 1995). One of these, the perceptual representation system (PRS) proposed by (Tulving & Schacter, 1990), is dedicated to the storage of structural properties of visual images, and is thought to consist of a number of different subsystems widely distributed in the brain. Damasio (1989) and Kosslyn (1994) have proposed that visual memory involves the reactivation of early visual representations through separately stored combinatorial codes. It is therefore possible that the neural subsystems or modules subserving visual processing of dimensions like colour, motion and form may also be part of the putative PRS memory system. Psychophysical studies point to a close relationship between perceptual discrimination and short- and long-term memory (Magnussen, *et al.*, 1990; Magnussen & Greenlee, 1992; Magnussen & Dyrnes, 1994; Magnussen, Greenlee, & Thomas, 1996), and PET studies have shown that areas of the visual cortex which are activated during visual perception are also activated during visual memory, under certain conditions even to the same degree (Kosslyn, *et al.*, 1993).

Psychophysical experiments further suggest that sensory and memory modules have access to independent

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but limited attentional resources. The results of dual-task experiments (Broadbent, 1982; Allport, 1989) in vision show that subjects can perform two perceptual discriminations concurrently whenever the task requires monitoring separate stimulus dimensions but not when it requires monitoring the same dimension in two stimuli. Wolfe, *et al.* (1990) found that visual search for conjunctions of color and orientation was much faster than search for conjunctions of two orientations or two colors. When subjects are asked to make two discriminations concurrently, they can do the task without mutual interference for different attributes (e.g., spatial frequency and orientation), but not for concurrent discriminations of the same attribute (e.g., two spatial frequencies; Allport, 1971; Wing & Allport, 1972; Stefurak & Boynton, 1986; Chua, 1990; Vincent & Regan, 1995).

In a variant of the concurrent discrimination task, Greenlee & Thomas (1993) measured discrimination thresholds for contrast and spatial frequency of sinusoidal gratings under conditions of stimulus uncertainty, where the stimuli varied randomly from trial to trial in contrast or spatial frequency. They found that subjects performed as well on a two-interval × two-alternative forced-choice task when they did not know along which dimension the two successively presented stimuli differed as when they did know, after the effect of added uncertainty was discounted. This independence between contrast and spatial frequency judgments is preserved in short-term memory, where simultaneous memory for spatial frequency and contrast obey different laws of memory decay but do not interfere with each other in a dual-memory task (Magnussen *et al.*, 1996). In a subsequent set of experiments we showed that independence between simultaneous visual discriminations only applies when subjects monitor contrast and spatial frequency, but not when they monitor two contrast or two spatial frequency components; discrimination thresholds were raised by a factor several times the threshold values of single-judgment control measurements (Magnussen & Greenlee, 1997). In both the same and different-attribute conditions, essentially the same results were obtained when the two components were part of the same stimulus in the form of a complex grating, and when they formed spatially separate gratings (Magnussen & Greenlee, 1997). Thus the interference observed in same-attribute dual-judgments is apparently not related to a spatial restriction of attention.

These results support a model of visual discrimination and short-term memory where stimuli are processed by a set of parallel special-purpose mechanisms devoted to basic stimulus dimensions. Independent but limited attentional resources are allocated to these mechanisms (Treisman, 1969; Magnussen *et al.*, 1996; Magnussen & Greenlee, 1997). Competition for processing resources might then occur when inputs are analyzed by the same mechanism, as in the case of judging two colors, two shapes, two contrasts or two spatial frequencies, but not when they are encoded by different mechanisms (e.g., for contrast and spatial frequency, spatial frequency and orientation, or all three dimensions; Chua, 1990; Greenlee & Thomas, 1993; Vincent & Regan, 1995; Magnussen & Greenlee, 1997).

In the present paper we ask two questions about the proposed special-purpose, limited-capacity mechanisms.

The *first* question concerns the location of the bottleneck on information flow. In the dual-judgment spatial frequency experiments (Magnussen & Greenlee, 1997) in which two reference gratings were presented simultaneously, the subject had to store this information for a brief interval of 1–3 sec and then compare the stored representation to the second pair of gratings. Under conditions where the subject has to judge which component changed and which interval contained the stimulus with the higher value on that component, discrimination thresholds increased by a factor varying from 3 to 6. The capacity limitation underlying such a rise in thresholds may be a property of the stimulus encoding or stimulus selection process, of the short-term storage, of the decision process, or of any combination of these factors. The decision process may produce higher discrimination thresholds even if perceptual encoding or memory does not limit performance. This is a statistical consequence of adding more sources of noise contributing to the decision by increasing the number of stimuli or dimensions. Greenlee & Thomas (1993) have developed a model for estimating the effect of stimulus uncertainty in this type of dual-judgment task, which allows us to isolate the contribution of the decision process. Assuming orthogonal representation of the different stimulus dimensions and stimulus-uncorrelated unit gaussian noise, their model predicts, under the conditions used, an increase in discrimination thresholds by a factor of 1.7, a factor which is closely matched by the mean trends in the data for contrast × spatial frequency judgments. This finding suggests that the observer optimally uses independent sources of information (on the relative spatial frequency and contrast of the first and second stimulus presentations) assuming uncorrelated gaussian noise (see their Figs 6–8). Keeping the number of stimuli and decisions constant, we have tested the hypothesis of an early bottleneck of information processing by comparing dual judgments of spatial frequency when the two reference gratings were presented simultaneously or with a short delay (i.e. stimulus onset asynchrony, SOA). A sufficiently long SOA should enable the subject to shift or refocus his or her attention (Stoffer, 1993), thereby allowing him or her to successively encode both stimulus components. The logic of this argument is analogous to that of dual-task reaction time experiments. In a dual task involving the discrimination of the mirror inversion of rotated letters and auditory tones, Ruthruff, Miller, & Lachmann (1995) found an effect of SOA, such that RTs were lower for a 400 msec SOA (first letter, then tone presentation) than for a 50 mse SOA. In the present study, if discrimination thresholds (reaction times) significantly covary with the SOA of the components of the reference pair, the bottleneck on information flow must be located prior to the memory and perceptual

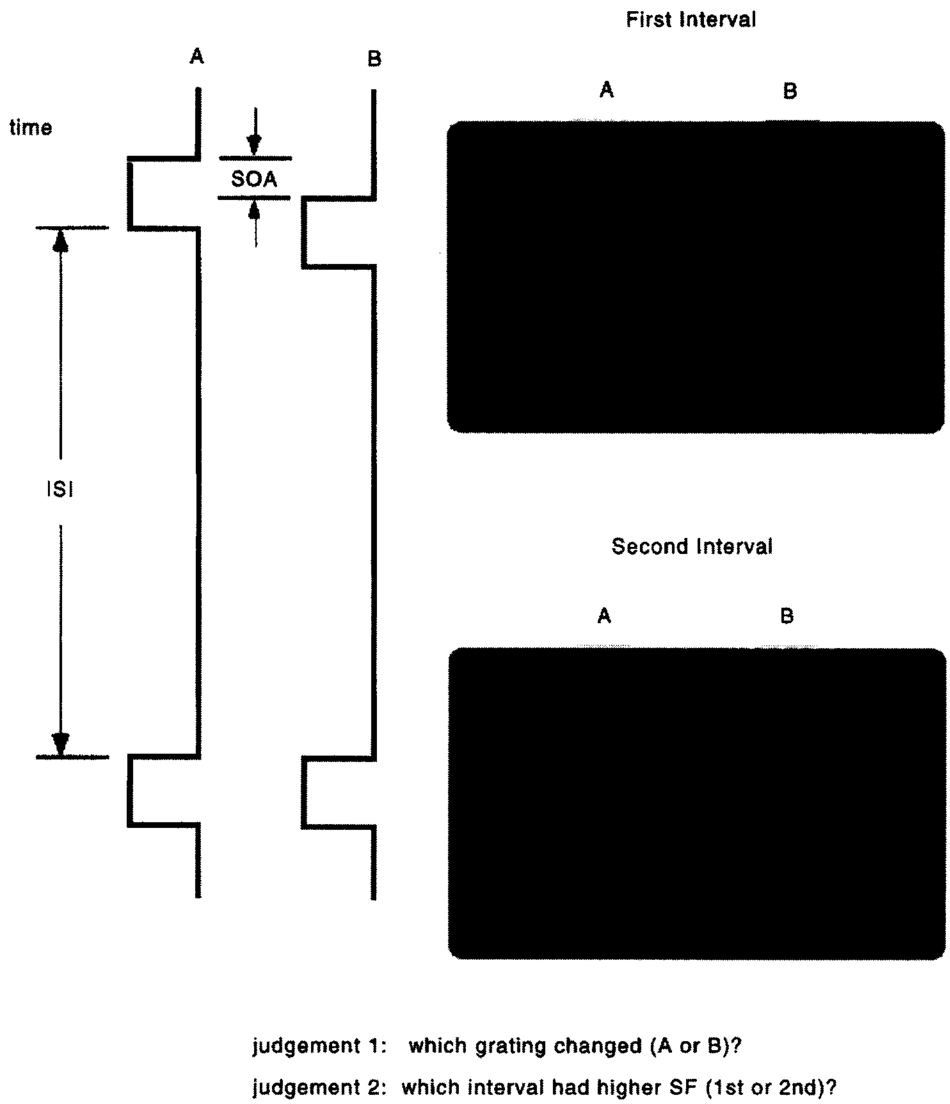

FIGURE 1. Schematic illustration of the experimental design. For more details see text.

decision stage. On the other hand, if SOA has no effect on thresholds and RTs, then it can be concluded that the bottleneck must be subsequent to encoding.

The *second* question concerns the specificity of the interference observed in the dual-judgment experiments. The hypothesis of dedicated attentional capacity implies that interference in same attribute, dual-judgment tasks reflects a general competition for processing resources between any two inputs to the same mechanism or module. But there is an alternative explanation of this finding, in terms of inhibitory interactions between subprocessors tuned to narrow ranges of spatial frequencies. This possibility is suggested by a series of experiments on memory masking (Magnussen *et al.*, 1990; Magnussen & Greenlee, 1992; Bennett & Cortese, 1996). In memory masking, delayed discrimination thresholds have been measured by a two-interval forced-choice task with a 10-sec interstimulus interval (ISI) between test and reference stimuli, in which a masker stimulus is briefly presented midway during the ISI. Under these conditions, discrimination thresholds were elevated, depending on the relative separation of the test, reference and masker stimuli along the dimension for which discrimination was required, but not their relative separation along other dimensions. For example, memory masking of spatial frequency depends on the relative spatial frequencies of the test, reference and masker stimuli, but not on their relative orientations (Magnussen, *et al.*, 1991). On a task where the subject judges the speed of moving stimuli, memory masking for motion depends on the separation in speed but not on the relative direction (Magnussen & Greenlee, 1992). From these earlier results, we concluded that discrimination and memory are based on higher-level representations or modules tuned to a single dimension, for example, spatial frequency, which extracts information across other dimensions, such as orientation or velocity. Adding the principle of dimension-specific inhibition (Nelson, 1985; Greenlee & Magnussen, 1988) this arrangement allows for both parallel, independent processing of separate attributes or dimensions, and predicts detrimental interactions between dimensions of the type observed in memory masking and possibly in experiments employing same-attribute, dual-judgments (Magnussen & Greenlee, 1997). In the present paper we have explored the stimulus specificity in dual-judgment interference by varying the relative spatial frequencies of the two component gratings.

METHOD

Figure 1 presents a schematic illustration of the experimental design. The details of the apparatus and experimental procedure have been described in previous papers (Greenlee & Thomas, 1993; Magnussen & Greenlee, 1997). Briefly, two sinewave grating strips, one to each side of a fixation point, were generated on a high-luminance (150 cd/m^2), high-resolution television display with a frame refresh-rate of 98 Hz (Joyce Electronics, Cambridge, U.K.). Both reference and test stimuli were truncated in space and time by one-dimensional gaussians with a space constant of 1.23 deg and a time constant of 100 msec, respectively. This space constant yields a strip width of 4.92 deg (95% of total contrast energy under spatial envelope). For spatial frequencies between 1.25 and 5.0 c/deg, this space constant produced relative bandwidths at half-height varying between 1.2 and 0.1 octaves, respectively. The time constant gives an effective exposure time of approximately 400 msec. Stimulus contrast at the peak of the gaussian envelope was 16%. The center-to-center distance of the gratings was 5.5 deg visual angle, when viewed from a distance of 84 cm.

Delayed discrimination thresholds for the two frequency components were measured in a four-alternative forced-choice (4AFC) paradigm, which used randomly interleaved staircases that were controlled by an adaptive procedure (the Best PEST, Lieberman & Pentland, 1982). In a dual-judgment trial, two reference gratings were briefly presented, followed by a 5-sec interstimulus interval (ISI) and the presentation of the two test gratings, one of which was randomly higher or lower than its reference. On each trial, the observer made one response on a two-lever response box (CB1, Cambridge Research Systems). The subject indicated which component had changed by selecting either the left lever to indicate that the left stimulus changed or by pressing the right lever to indicate that the right stimulus changed. At the same time the observer indicated whether the selected stimulus had a higher value in the first or second interval by pressing the lever either forwards or backwards (forwards—first interval; backwards—second interval). The left lever was manipulated by the left thumb and index finger, whereas the right lever was moved using the right thumb and index finger. Sufficient practice was allowed prior to recording sessions to ensure that the subjects understood the task and could properly operate the response box. The response procedure was held constant throughout the investigation. The subjects were informed that both accuracy and reaction times were recorded. The observer's response on a given trial was scored as correct, when both aspects of the response were correct, in all other cases the trial was scored as incorrect. Auditory feedback in the form of a brief tone was given after each trial. The tone was high if the response was correct and low if the response was incorrect. The subject had 2 sec to respond. Timed-out trials were placed back into the trial pool and were conducted again at a later point in the run, which was seldom necessary.

The response information gained on each trial (correct–incorrect) was passed to the PEST algorithm, which then selected the stimulus value for the next presentation of that condition. The spatial frequency difference between the test and reference stimuli was controlled on a 40-step staircase, where the upper and lower bounds were adjusted so that the threshold values were approximately midway between these bounds. More precisely, the PEST procedure returned an integer value ranging from 1 to 40. This integer was then used to determine the size of the ΔSF such that the test SF was equal to:

$$SF_{\text{test}} = SF_{\text{ref}} \pm (SF_{\text{ref}} * (0.01 * p)),$$

where p is the integer returned by the PEST procedure. A single run consisted of 80 trials, 40 trials per staircase. Chance performance was 25% correct and the discrimination threshold was defined with reference to the 62.5% level of performance. These values are expressed as Weber fractions ($\Delta SF/SF_{\text{ref}}$).

The experimental parameters investigated were the relative spatial frequencies of the two gratings and the stimulus onset asynchrony (SOA) of the left and right gratings, in an experimental program encorporating a matrix of four spatial frequency differences and five SOA conditions.

To vary the relative spatial frequency of the components, one spatial frequency was fixed at 5 c/deg (high SF) and the frequency of the second grating varied between 1.25 and 5 c/deg in half-octave steps (low SF). The position of the high and low spatial frequency gratings with respect to visual field (left or right) was fixed during runs but varied in a counter-balanced fashion between runs. Thus, the subject always knew which grating appeared in which visual field. The exception to this rule is the case of zero spatial frequency difference, where both reference gratings had a spatial frequency of 5 c/deg. To prevent the subjects from making discriminations on the basis of position cues, the spatial phase of both components was random over trials. To exclude the possibility that the subject could learn to identify a fixed SF_{ref} over repeated trials, on each trial we randomly "jittered" the reference spatial frequency. A random number generator picked a number ranging from -10 to 10 and this value served to increment or decrement the SF_{ref} such that:

$$SF_{\text{ref}}(i) = SF_{\text{ref}} + SF_{\text{jitter}},$$

where $SF_{\text{ref}}(i)$ was the reference frequency on trial i and

$$SF_{\text{jitter}} = SF_{\text{ref}} * (0.01 * rand(-10, 10)).$$

This procedure was performed on each trial prior to determining the value of ΔSF.

The left and right reference gratings were presented either simultaneously or with a SOA of 100, 200, 400 or 800 msec (see Fig. 1); the test gratings were always presented simultaneously. Which of the two reference frequency components (left or right) was leading varied from run to run, but was fixed within runs. Thus, half the time the low frequency component was leading and half the time the high frequency component was leading.

Reaction times were measured using the frame counter of the stimulus generator board (VSG 2/3), which give a high precision of time recording (resolution 10 μsec) and synchronizes the onset of the time period to the frame sync of the display. Owing to the expected skewed distribution of reaction times, all statistical analyses were performed on the logarithm of reaction time. Three observers participated, author MWG, and two naïve observers who were paid for their participation. Author MWG is a left-handed male, observers LB and NP are right-handed females.

RESULTS

Analyses of variance (ANOVA) for repeated measures were performed on discrimination thresholds and the logarithm of the choice reaction times (log RT). The within-subjects main effects of SOA (five levels of delay), spatial frequency (low–high SF), spatial frequency difference (four levels), order of presentation (low or high SF first), position of the low and high spatial frequency components, as well as their respective first- and second-order interactions were analyzed. We could also estimate the across-subjects effect by entering the Observer as a main effect. The variance across repetitions of the experiment runs ($n = 3$) could thus be used in the error term for this effect.

The effect of observer

The observer effect was not significant for the dependent variable $\Delta f/f$ ($F(2,37) = 0.6$; $P = 0.55$), nor were any of the first-order interactions between the observer and the other main effects significant. Contrary to this, the observer effect was highly significant for log RT ($F(2,27) = 37.99$; $P = 0.0001$), but the observer effect did not interact with the other experimental variables. Observer LB exhibited the lowest RT with a geometric mean of 851 msec (SD = 201.5 msec) averaged over all other conditions, followed by observer MG (geometric mean RT = 1241 msec, SD = 218 msec) and observer NP (geometric mean RT = 1406 msec, SD = 154.7 msec). Significant inter-individual differences in choice RT on a similar spatial frequency discrimination task have been reported by Greenlee & Breitmeyer (1989). Compared with that earlier study, the reaction times reported here are a factor of two or more greater, which reflects the additional processing required to discriminate two spatial frequencies. The possible trade-off between speed and precision is discussed below.

The effect of SOA

The effects of the timing of the left and right gratings on precision and speed of responses are shown in Fig. 2, plotting, in (a) and (b), Weber-fractions and choice RTs as functions of SOA for the high and low frequency components separately. Discrimination thresholds for the high SF component (5.0 c/deg) are given by the filled symbols, while thresholds for the low SF component are shown by the open symbols. The order of presentation of the high and low SF components are shown by the different symbols.

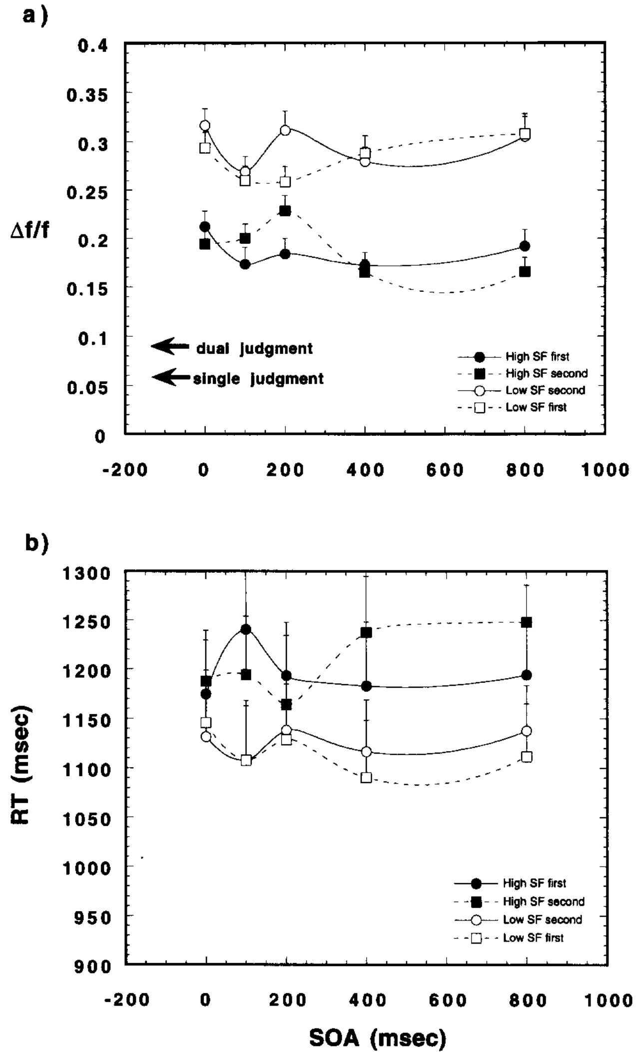

FIGURE 2. Discrimination thresholds (a) and choice reaction times (b) in the dual-judgment of spatial frequency differences as a function of the stimulus onset asynchrony (SOA) of the high and low spatial-frequency component grating. Results are the mean values of three observers, averaged over four reference frequency combinations and three repetitions; the high SF component represents 5 c/deg, the low SF component represents data averaged over 1.25, 2.5 and 3.54 and 5.0 c/deg reference spatial frequencies. Circles give the results for the conditions where the high SF-component was leading, the squares give the results for the condition in which the high SF-component was trailing, during the presentation of the reference pair. Error bars show +1 SE.

The discrimination thresholds in the dual task condition are four to six times higher than normally reported for spatial frequency discrimination of spatially enveloped gratings presented for this combination of spatial-

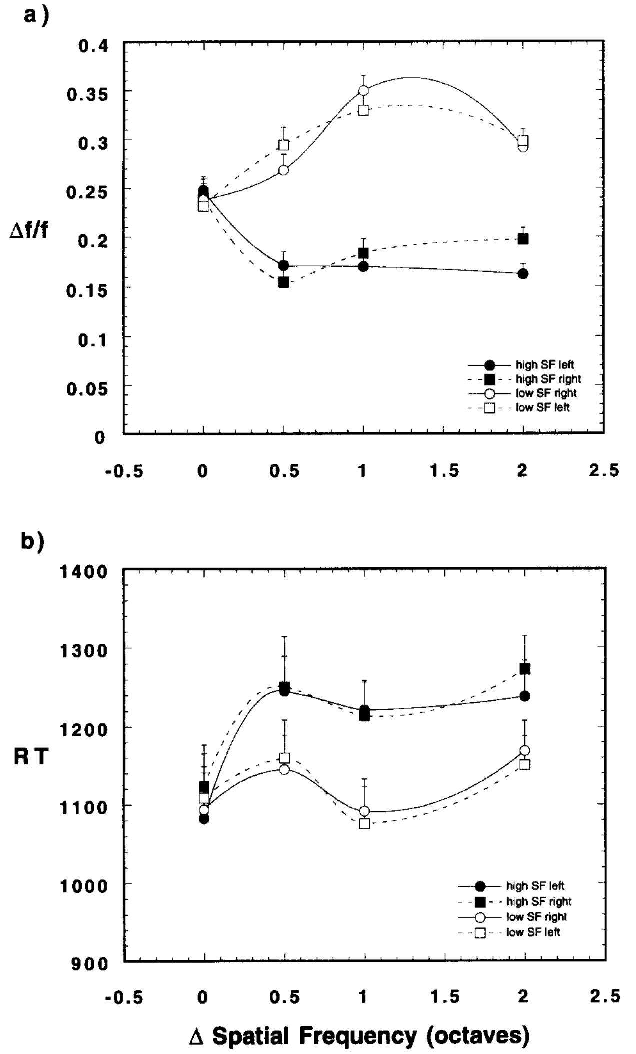

FIGURE 3. Discrimination thresholds (a) and choice reaction times (b) in the dual-judgment of spatial frequency as a function of the difference in spatial frequency (in octaves) between the left and right reference grating. The high SF was fixed at 5 c/deg, while the low SF varied between 1.25 and 5 c/deg over separate runs. Circles present the results when the high SF component was presented in the LVF (low SF component in the RVF), and squares present the results when the high SF component was presented in the RVF (low component in LVF). Results are means of three subjects and are averaged over delay conditions. Error bars show ±1 SE.

frequency bandwidth, contrast and eccentricity (Weber fractions usually less than 0.05; (Greenlee, 1992)) and found by us for discrimination of single gratings under the present conditions (Magnussen & Greenlee, 1997). For comparison, the mean discrimination threshold, measured in a conventional single-judgment condition where the subject knows which component changes, is taken from Magnussen & Greenlee (1997); means of three subjects, see lower arrow in (a). The predicted threshold, based on the uncertainty associated with the dual-judgment task, is indicated by the upper arrow. This factor is calculated according to a model based on statistical decision theory for independent sources (Greenlee & Thomas, 1993), which here can serve as the reference value for evaluating the threshold elevation related to interference or to limited processing capacity in the dual-task situation. Clearly, the dual-task discrimination thresholds exceed this value for both frequency components.

At all SOAs discrimination was better for the higher reference spatial frequency in the grating pair ($F(1,4) = 61.62$, $P = 0.0001$). Since spatial frequency discrimination thresholds for single-frequency, band-limited grating patches remain quite stable for spatial frequencies between 1 and 4 c/deg at 5 deg eccentricity (Fig. 6 in Greenlee, 1992), this difference must be related to other aspects of the present experiment. One possible factor could be tied to our use of a fixed space constant which defined the stimulus envelope. The lower spatial frequency component would thus have a greater SF-bandwidth, which could create a bias effect discussed below.

The main effect of SOA was significant for the discrimination thresholds ($F(4,8) = 3.2$; $P = 0.015$). Although the effect of SOA is significant, the trends are not very consistent across subjects. Observer LB shows little effect of SOA, observer MG shows higher thresholds at a SOA of 200 msec for the lower SF component, but only when it is presented trailing the high SF component. Also, observer NP shows some evidence for lower $\Delta f/f$ values under the 100 msec SOA condition. Although the main effect of the order of presentation of the individual SF components was not significant ($F(1,39) = 1.23$, $P = 0.27$), there is a significant three-way interaction between the factors: delay, relative spatial frequency, and order ($F(4,156) = 4.94$; $P = 0.0009$). This interaction implies that the shapes of the curves differ across conditions. These differences are not, however, consistent across subjects.

The RT data [Fig. 2(b)] present a similar picture, except that the curves for the high and low reference spatial frequencies exchanged position. Shorter RTs are associated with the low spatial frequency component and high discrimination thresholds, whereas longer RTs are associated with the high spatial frequency component and low discrimination thresholds, in agreement with an earlier study (Greenlee & Breitmeyer, 1989). The possibility that this relationship reflects a speed–precision trade-off is examined below. The difference in log RT to the high and low frequency gratings is highly significant ($F(1,2) = 28.8$, $P = 0.0001$), but there was no effect of SOA on logRT ($F(4,116) = 0.08$, n.s.). No order effects were observed ($F(1,29) = 0.003$, n.s.) nor was there a significant interaction between spatial frequency and order of presentation ($F(1,2) = 0.88$, n.s.).

The effect of spatial frequency difference

Figure 3 is based on the results shown in Fig. 2, but now thresholds are plotted as a function of the difference in spatial frequency of the high and low reference gratings; Weber-fractions ($\Delta f/f$) and RTs are shown in (a) and (b), respectively. The different symbols show the results for the conditions in which the high SF-component was in the left (circles) or right (squares)

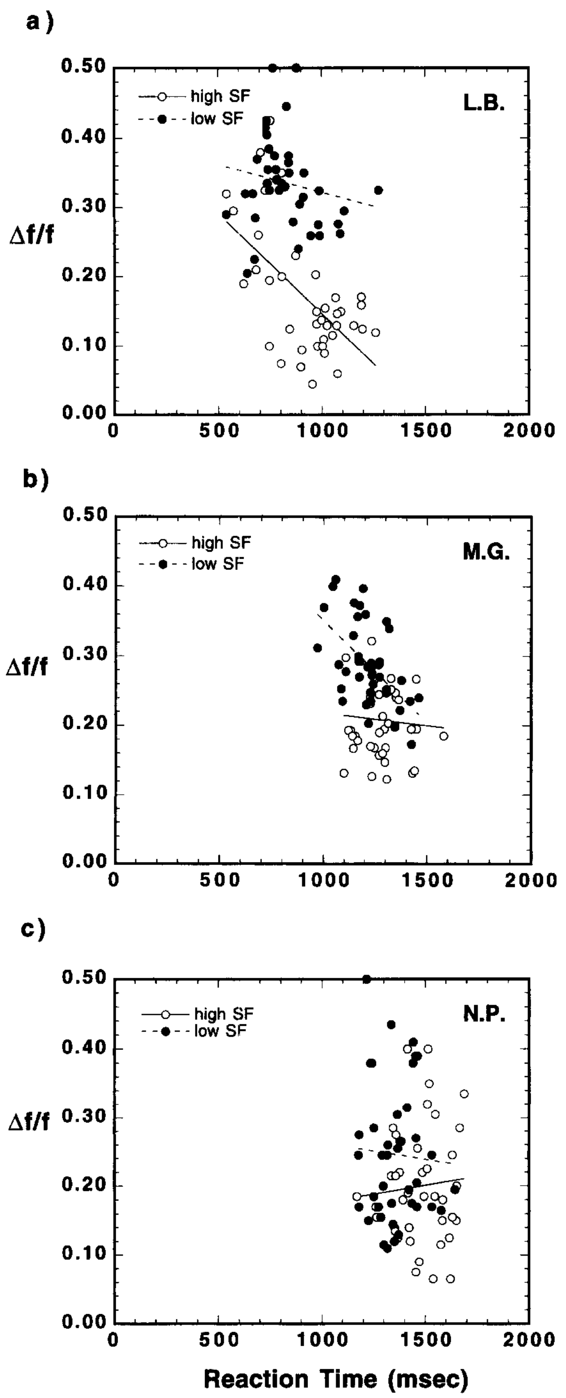

FIGURE 4. Scatterplots of discrimination thresholds vs choice reaction times for all individual runs, for each subject. Results for the conditions where there was a change in the low spatial frequency component are indicated by filled symbols, those for the conditions with a change in the high spatial frequency component by open symbols.

visual field. When the spatial frequencies of the reference gratings match ($\Delta SF = 0$ octave), discrimination thresholds and reactions times, though measured for each component separately, are necessarily similar for the two component gratings. As the difference in spatial frequency between the reference gratings increases, discrimination thresholds decrease for the high spatial frequency component and symmetrically increase for the low frequency component. This trend is confirmed by the ANOVA showing no main effect of spatial frequency difference ($F(3,36) = 0.64$, $P = 0.6$) but a highly significant interaction between reference frequency (high or low SF component) and spatial frequency difference ($F(3,36) = 8.02$, $P = 0.0003$). For observer LB, the largest differences in thresholds are evident for an 0.5 octave step, whereas observers MG and NP show the largest difference at 1 octave difference.

The results for RTs are fairly independent of the spatial frequency difference between component gratings. Observer LB exhibits higher RTs as the SF difference increases, but observers MG and NP do not show this effect. The main effect of the spatial frequency difference on log RT was not significant ($F(3,26) = 0.15$, $P = 0.87$), but the interaction between reference spatial frequency (high or low SF component) and the spatial frequency difference was highly significant ($F(3,26) = 5.6$, $P = 0.004$). This interaction indicates that when the two components differ in spatial frequency, the choice RTs are lower on trials in which the relatively lower SF-component changed.

The effect of position of high and low spatial frequency components

Our systematic variation of the position of the high and low spatial frequency components allowed us to test whether the observed differences in thresholds and RTs depended on the location of individual components in the visual field. It has been suggested that the left hemisphere more efficiently processes high spatial frequencies, whereas the right hemisphere processes low spatial frequencies better (Friedman & Polson, 1981; Sergent, 1982; Kitterle, Christman, & Hellige, 1990; Kitterle, Christman, & Conesa, 1993). Such an asymmetry would be expressed in a significant interaction between the factors position (LVF, RVF) and relative spatial frequency (high, low SF component). As can be seen in Fig. 3, the relative positions of the high and low spatial frequency components had little effect on the overall trends in the data. During each run, the position of the high and low SF-components was fixed. Thus, there was no positional uncertainty within each run with respect to the side of component presentation. Such position uncertainty might enhance hemispheric differences. Other studies have indicated that the hemispheric differences in the processing of low and high spatial frequencies might be related to a systematic response bias (Peterzell, Harvey, & Hardyck, 1989), and thus not to genuine differences in discriminability.

Also evident in Fig. 3 is the observation that the relative position of the high and low spatial frequency component had little effect on the observer's reaction time. The main effect of position of the high SF component is not significant ($F(1,28) = 0.01$, n.s.) nor is the important three-way interaction significant between the relative spatial frequency (high, low SF), the spatial frequency difference and the position of the high SF component in the visual field ($F(4,22) = 0.3$, n.s.).

Speed–precision analysis

The mirror symmetric pattern of results obtained for discrimination thresholds and choice RTs suggests that speed and precision might enter a trade-off relationship in dual-judgment spatial frequency discriminations. Relevant data on this question are given in Fig. 4. Since the Best-PEST procedure selects values of spatial frequency difference that should yield a fairly constant level of performance (62.5% in the present paradigm), the thresholds are more relevant here than the total number of errors (which remain more or less constant over runs).

Figure 4 summarizes the individual results by plotting $\Delta f/f$ as a function of RT for the three subjects separately. Subject NP spends, on average, 555 msec more on the perceptual decisions than observer LB (although they are of the same age). To evaluate the speed–accuracy relationship, correlation analyses were performed on the individual data converted to standardized z-scores. The correlations between discrimination thresholds and choice RT were -0.48 ($P = 0.0001$) for observer LB who showed the largest differences in thresholds between the high and low frequency component, -0.41 ($P = 0.0002$) for MG who showed the second largest difference, and -0.096 ($P = 0.39$) for NP who showed the smallest difference in thresholds for the two components. Thus, a speed–precision trade-off does enter the results of the individual subjects. This aspect of the results will be considered in more detail below.

Error analysis

The results presented above indicate that the effects of the timing of the presentation of the left and right component of the reference gratings, as well as the SOA, had only a small effect on discrimination thresholds, compared with the overall effect of the dual judgment task itself (Fig. 2). The symmetric deviation of the curves for the low and high reference spatial frequency components with increasing spatial-frequency difference suggests that a strategy may be involved where subjects attend more to the higher spatial frequency whenever the two components differ. Such strategies have been observed in other experiments (Greenlee & Thomas, 1993) and can be brought to light by an analysis of the errors made in the 4AFC task. In this experimental design three types of errors have equal statistical probabilities: (1) correct stimulus, incorrect interval; (2) incorrect stimulus, correct interval; and (3) both stimulus and interval incorrect. For the high spatial frequency component, the errors were fairly evenly distributed among the three categories, but for the low spatial frequency component type 3-errors were grossly over-represented and together with type 2-errors account for about 85% of the total errors. This trend is statistically significant in the 2×3 contingency coefficient $C = 0.453$, $df = 2$, $P < 0.001$ (Siegel, 1956). Thus, when in doubt the subject often appears to have chosen the high frequency component, which acts to increase both type-2 and type-3 errors on trials where the lower spatial frequency changed, as well as to increase correct performance on trials where the high spatial frequency component changed. The results of this analysis also indicate that the response bias enters whenever the two components differ in spatial frequency and is not related to the octave difference on the frequency dimension (3×4 contingency coefficient, $C = 0.036$; n.s.).

DISCUSSION

When subjects discriminate two stimulus components with respect to the same attribute or dimension, the thresholds for both components are raised by a factor of four to six compared with single discriminations on the same dimension. This result suggests that the task overloads a limited-capacity discrimination process (Magnussen & Greenlee, 1997). The present experiments show that the bottleneck in the information flow required for this performance is most likely not the stimulus selection or encoding process, since the performance did not improve by much when the presentation of one of the two reference gratings was delayed in time. Such a delay should have allowed the subject to shift attention and refocus to another spatial scale (Stoffer, 1993), thereby permitting serial encoding of the two reference spatial frequencies (Fig. 2). Furthermore, ANOVA revealed that the order in which the stimulus components were presented did not have a significant main effect on discrimination thresholds. There was a significant third-order interaction between the effects of delay, order, and relative spatial frequency, such that the shape of the $\Delta f/f$ by SOA curves differed depending on whether the component was trailing or leading during the presentation of the reference pair. However, the shapes of the curves differ over subjects, making interpretation of this interaction difficult.

The results further indicate that the interference arising in same-attribute, dual-judgment tasks is not stimulus-specific. First, the discrimination thresholds averaged across the two SF components do not significantly change with the spatial frequency difference of the left and right gratings. It is not, on average, easier to discriminate the spatial frequency of side-by-side gratings two octaves apart than to discriminate gratings 0.5 octave apart or gratings that match in spatial frequency. When the two frequency components differ a response bias enters into the results, which acts to lower the discrimination thresholds for the relatively higher frequency component (here 5 c/deg) and raise the thresholds for the lower frequency component by a corresponding amount, but this effect is, for the most part, independent of the exact spatial frequency of the lower component over the 2.0 octave range tested.

Our use of a constant spatial envelope size led to a variable spatial-frequency bandwidth for the different reference frequencies: higher spatial frequencies were always associated with narrower bandwidth and thus more specific information about the dimension was present. It might be argued that this aspect of the experimental design favored the high SF component.

However, the fact that the interference effect did not vary much with the spatial frequency difference speaks against this interpretation. In an earlier study, Greenlee (1992) showed that the spatial frequency discrimination of eccentrically presented gratings depended both on stimulus contrast and stimulus bandwidth. However, for high contrast levels, stimulus bandwidth only affected performance when the bandwidth exceeded one octave. In the present study, this only occurred for the lowest spatial frequency tested (1.25 c/deg with a bandwidth of 1.2 octaves).

The type of interference arising in our task therefore seems to reflect a competition between inputs processed by the same mechanism, and is not related to the relative values of the inputs on the dimension in question. This suggests a different form of interaction than observed in memory-masking (Magnussen *et al.*, 1991; Magnussen & Greenlee, 1992; Bennett & Cortese, 1996), in which delayed spatial frequency thresholds are affected by presenting a third grating during the interstimulus interval. In memory masking, no active processing requirements are imposed on the observer with respect to the masker. Nevertheless, discrimination thresholds are doubled under conditions of maximum masking, an effect which, however, is much less than the effects observed in the present study. Memory masking depends on the relative spatial frequencies of the test, reference and masker gratings, whereas the present effects do not (Fig. 3). It is likely that memory masking reflects inhibitory neural interactions at an earlier processing stage (Magnussen *et al.*, 1991; Magnussen & Greenlee, 1992), and if operating in the present experiment, they are camouflaged by the more powerful interference effects arising from the active processing of the spatial frequency information.

How limited is this form of dimension-dedicated attention? It is quite possible that the capacity of these mechanisms is only able to code a single input, and that two inputs are never handled together. Subjects may on a given trial select one component for attention and switch attention between left and right gratings from trial to trial. Thresholds would then be higher simply because the subjects only attended to the critical stimulus on half the trials and were forced to guess about the second grating. The response bias demonstrated by the error distributions indicates that such cognitive strategies might be involved. We cannot, on the basis of the present results, exclude the attention switching hypothesis but the absence of a prominent order effect in the different SOA conditions speaks against it. Experiments on concurrent discrimination where decisions on both components are required on each trial (Wing & Allport, 1972; Duncan, 1993) indicate that concurrent discriminations may be made, although performance is impaired. Since the reported data are averaged across a large number of trials, the strategy outlined above might be used by the subjects on individual trials in dual-task experiments (LaBerge, 1990). In a different type of experiment on the effect of memory set size on discrimination thresholds of line length, Palmer (1990) evaluated the attention switching hypothesis and rejected it, since test target values were found to produce almost perfect accuracy of discrimination with a four-item set size where the all-or-none attention-switching hypothesis predicts a maximum performance of 62.5% correct. Other experiments have also shown that when the perceptual judgment is easy, two judgments may be carried out concurrently without interfering with each other (Farell & Pelli, 1993). The two explanations are not mutually exclusive, they may coexist and an attention switching strategy may assist solving the task when difficulty is increased, as in the present study, when the test–reference differences approach threshold values.

Choice RTs and discrimination thresholds exhibit the same pattern of results except that their positions are exchanged, with longer RTs associated with detection of a change in the high-frequency component. This suggests a trade-off between time and precision, and an analysis of the individual data indicated a moderate, negative correlation for two of the three subjects studied. Other factors may contribute to this relationship. In a much simpler task (consisting of a single test and reference grating whose frequencies were 0.25 or 0.125 octaves apart), Greenlee & Breitmeyer (1989) found that choice RTs were longer for discriminations at 5 c/deg reference frequency compared with lower frequencies. In that experiment the task was a two-interval forced-choice discrimination and choice RTs were in the order of 400–500 msec; in the present 4AFC much longer choice RTs were measured, which reflects the complexity of the decision. Greenlee & Breitmeyer (1989) estimated the decision time for spatial frequency discrimination by subtracting simple RT from choice RT, and found values at 5 c/deg around 300 msec. A rough estimation of the decision times in the 4AFC task based on the Greenlee & Breitmeyer (1989) data for simple RTs would be in the order of 900–950 msec for the 5 c/deg component in the dual-discrimination task when the the left and right gratings have different reference frequencies. This suggests that the effect of complexity defined by the number of possible outcomes (four alternatives) acts additively on decision times. In the simplest scheme, decisions are completed serially with approximately 250 msec spent per alternative in an exhaustive search, which in some ways is analogous to memory scanning (Sternberg, 1975; Chase, 1986). Further comparisons of choice reaction times in 2AFC and 4AFC discrimination tasks and same-attribute and different-attribute dual-judgments within the latter condition should further clarify the relationship between discrimination and decision processes.

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