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# What limits simultaneous discrimination accuracy?

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## Abstract

Discrimination accuracy decreases when viewers simultaneously monitor two perceptually distinct stimulus components for changes in a common property, e.g. contrast [Magnussen & Greenlee (1997). *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 1603–1616; Olzak & Wickens (1997). *Perception*, *26*, 1101–1120]. We ask whether the limitation is in monitoring two components or in making dual decisions about a single property. Using the same uncertainty paradigm as Magnussen and Greenlee, we find no evidence of a processing limitation when viewers simultaneously monitor one component (1.25 c/d) for a possible change in contrast and a second component (5 c/d) for a possible change in spatial frequency, regardless of whether the components are spatially separated or superimposed. The limitation is in making dual decisions about a single property.

*Keywords:* Divided attention; Discrimination; Contrast; Spatial frequency; Uncertainty

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## 1. Introduction

Many perceptual judgments tap multiple sources of information, e.g. judgments of size and distance may use information provided by retinal image size, linear perspective, motion parallax, etc. Thus, it is important to identify processing limitations which reduce the ability to use multiple sources of information.

When viewers monitor a single grating patch for small changes in its several dimensions (contrast, spatial frequency, orientation, etc.), multiple judgments are made without loss of accuracy due to processing limitations, and concurrent judgments are stochastically independent of one another (Chua, 1990; Greenlee & Thomas, 1993; Magnussen & Greenlee, 1997; Olzak & Wickens, 1997; Vincent & Regan, 1995). However, when viewers monitor two perceptually distinct components for small changes on a common dimension, e.g. spatial frequency, discrimination accuracy is reduced by processing limitations (Magnussen & Greenlee, 1997; Olzak & Wickens, 1997). In the case of components which differ in spatial frequency, the overall magnitude of the reduction is little affected by whether the components are spatially superimposed or separated (Magnussen & Greenlee, 1997); nor, in the case of spatially separated components, is the magnitude of reduction affected by whether the components have the same or different spatial frequencies (Greenlee & Magnussen, 1998). This pattern of results is open to two alternative interpretations: (a) that accuracy decreases when viewers monitor two spatial locations or two spatial frequency bands; or (b) that accuracy decreases when viewers make dual evaluations about a single stimulus dimension. The present experiments address this ambiguity by having viewers monitor one component for a change in contrast and a second component for a change in spatial frequency.

Magnussen and Greenlee (1997) proposed that there is a separate mechanism which monitors each stimulus dimension for small changes, that the mechanisms for

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different dimensions operate independently and in parallel, but that each mechanism is internally limited in the sense that it can mediate only a single discrimination judgment at a time without loss of accuracy. This proposal predicts that no losses due to processing limitations should occur when viewers monitor two components, provided that each is monitored for changes in a different dimension. Using the same uncertainty paradigm and stimulus conditions as Magnussen and Greenlee, the present research tests this prediction and finds no evidence of processing limitations when the two components are monitored for different dimensions.

In the present experiments, the stimulus display always contains two grating patches, differing by two octaves in spatial frequency and, in some conditions, by several degrees in spatial location. On any given trial, one patch changes in contrast or the other patch changes in spatial frequency. In certainty conditions, the viewer knows which patch will change and need monitor only that single patch and stimulus dimension in order to judge the change. In uncertainty conditions, the viewer does not know which patch will change and must monitor both patches and both stimulus dimensions. Given that judgment accuracy is limited by noise, accuracy must be reduced to some extent in the uncertainty condition, even if no processing limitations constrain the ability to monitor both patches at once (Tanner, 1956). The magnitude of this inherent, noise-driven reduction in accuracy has been quantitatively modeled for discrimination experiments of the type used here, and the predictions of the model have been found accurate (Greenlee & Thomas, 1993; Magnussen & Greenlee, 1997; Thomas & Olzak, 1996). Thus, the empirical question is whether the reduction in accuracy observed in the uncertainty condition is greater than the expected noise-driven effect. If so, there is evidence that processing limitations constrain the ability to monitor separate components, even when separate dimensions are involved. If only the noise-driven effect is observed, the concept of independent, but internally limited, processing mechanisms for each dimension is supported.

## 2. Methods

Each stimulus comprised two vertical sinusoidal grating strips with spatial frequencies centered on 1.25 and 5.0 c/d and contrasts centered on 0.1. The strips were windowed horizontally by a Gaussian with a space constant of 1.23 deg and temporally by a Gaussian with a time constant of 100 ms. The strips modulated a 20° by 13.3° field of 100 cd/m$^2$ and extended the full height of the field. In separate conditions, the strips were spatially superimposed and viewed centrally or presented side by side with centers located 2.25° to either side of a fixation point. The stimuli were viewed binocularly and, except as noted below, from a distance of 0.84 m.

The task was to detect a change in either the contrast of the low frequency grating or the spatial frequency of the high frequency grating. Discrimination thresholds were measured using a two-alternative temporal forced choice: the stimulus was presented twice on each trial and the value of one component/dimension was changed slightly between the first and second presentations, which were separated by 1 s. The observer identified the change as described below. The magnitude of the change was adjusted from trial to trial using the best-PEST maximum likelihood search procedure to estimate the threshold (Lieberman & Pentland, 1982). Each staircase was 40 trials in length and produced 8–12 reversals. Small random variations were used to prevent learning of specific stimuli during repeated trials. The reference contrast of the 1.25 c/d component was varied from trial to trial between 0.09 and 1.10; the reference frequency of the higher component was varied between 4.5 and 5.5 c/d; and the phase of both components, with respect to the spatial envelope, was varied.

In the certainty or single-response condition, only one component/dimension was varied during a block of trials and was identified to the observer before the block began. The observer made a single response on each trial, identifying the change as an increase or decrease. Threshold was defined as 75% correct. Thresholds for contrast and spatial frequency changes were measured in separate blocks of 40 trials each.

In the uncertainty or dual-response condition, the component/dimension varied was randomly alternated from trial to trial and the observer had no foreknowledge of which would vary on a given trial. The observer made a two-part response: one part indicated which component/dimension had changed, the other part indicated whether the change was an increase or decrease. The response was made by pushing one of two levers, one for each component, forward or backward to indicate an increase or decrease. The response was counted correct only if both parts were correct. Under this scoring, chance was 25% correct and threshold was defined as 67.5% correct. Two interleaved staircases were run, one each for contrast and spatial frequency, and each block of trials consisted of 80 trials. A rest period occurred after the first 40 trials.

The design of the experiment was factorial, the variables being dimension judged (contrast or spatial frequency), stimulus configuration (superimposed or side-by-side), and judgment condition (certainty or uncertainty). Each subject completed three to six replications of each condition. Two of the five subjects, SM and MG, are authors; the other three subjects, EM, ST and AS were thoroughly practiced, but naïve to the purposes of the experiment. All had normal vision or were corrected for the viewing distance used.

Table 1

| Subject | Spatial frequency | | | | Contrast | | | |
|---|---|---|---|---|---|---|---|---|
| | Side-by-side | | Superimposed | | Side-by-side | | Superimposed | |
| | Cert | Uncert | Cert | Uncert | Cert | Uncert | Cert | Uncert |
| SM | 0.043 | 0.087 | 0.090 | 0.107 | 0.140 | 0.313 | 0.173 | 0.300 |
| EM | 0.067 | 0.173 | 0.157 | 0.267 | 0.207 | 0.307 | 0.34 | 0.213 |
| MG | 0.067 | 0.170 | 0.047 | 0.130 | 0.073 | 0.100 | 0.113 | 0.093 |
| ST | 0.069 | 0.114 | 0.080 | 0.093 | 0.211 | 0.323 | 0.155 | 0.267 |
| AS | 0.060 | 0.132 | 0.185 | 0.142 | 0.140 | 0.350 | 0.210 | 0.27 |
| Mean | 0.061 | 0.135 | 0.112 | 0.148 | 0.154 | 0.279 | 0.198 | 0.229 |
| SE | 0.005 | 0.016 | 0.026 | 0.031 | 0.026 | 0.045 | 0.039 | 0.037 |

Two subjects, ST and AS were run at a viewing distance of 1.1 m. For these subjects, the spatial frequencies of the grating components were 1.64 and 6.55 c/d and the space constant of the Gaussian window was 0.94 deg.

The threshold obtained in each block of trails was converted to a Weber fraction, i.e. threshold frequency (or contrast) deviation divided by the reference frequency (or contrast). The data in Table 1 are linear means of these fractions. Analysis of variance was conducted on logarithms of the fractions. Logs were used for two reasons: (1) to resolve the scaling problem in comparing discrimination thresholds for contrast and spatial frequency; and (2) because the primary interest of the experiments is the proportionate increase in thresholds between certainty and uncertainty conditions, i.e. whether thresholds rise by a greater factor than noise alone would predict. The analysis was conducted using three fixed within subject variables: dimension judged (spatial frequency or contrast); stimulus configuration (side-by-side or superimposed); and judgment condition (certainty or uncertainty). Subjects were treated as a fourth, random variable. The means and standard errors shown in Fig. 1 were computed using the log values.

## 3. Results

Table 1 presents mean results for each subject and condition and the averages for all subjects. As found in other studies (Greenlee & Thomas, 1993; Magnussen & Greenlee, 1997), thresholds (expressed as Weber fractions) for contrast discrimination are higher than those for spatial frequency discrimination ($P = 0.0235$), although the magnitude of the difference varies from one observer to another (subjects × dimension interaction, $P = 0.0106$). There is no consistent difference between results obtained with the side-by-side and superimposed configurations, although individual observers did find one configuration more difficult than the other (subjects × configuration interaction, $P = 0.0124$).

As found in other studies, thresholds are higher in the uncertainty conditions than in the certainty conditions ($P = 0.0004$, no significant interactions). Averaged over dimensions, configurations, and subjects, thresholds are higher in the uncertainty condition by a factor of 1.62, which is within measurement error of 1.69 ($t = 0.56$), the factor expected for a purely noise-determined uncertainty effect (Greenlee & Thomas, 1993). Fig. 1 provides a more detailed presentation of the uncertainty effect. Each data point represents the two means for an individual subject for a single dimension and stimulus configuration. The

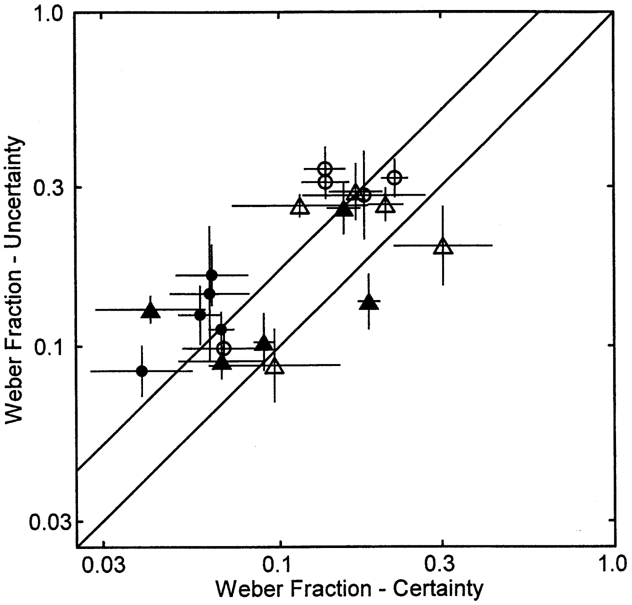

Fig. 1. Comparison of thresholds in the certainty and uncertainty conditions. Each data point represents the two means for one subject judging one dimension in one stimulus configuration. The abscissa is the threshold in the certainty condition, the ordinate is the threshold in the uncertainty condition. The lower diagonal line is the locus of equal thresholds. The upper diagonal line is the expected locus of thresholds when only noise-driven uncertainty reduces performance. Processing limitations would push the thresholds above the upper line. Filled symbols represent spatial frequency judgments, open symbols contrast judgments. Circles represent the side-by-side configuration, triangles the superimposed configuration.

abscissa of the data point represents performance in the certainty condition, while the ordinate represents performance in the uncertainty condition. The lower diagonal is the locus of equal performance in the two conditions. Nearly all the data points lie above this line and represent poorer performance in the latter condition. The upper diagonal line is the locus predicted for noise-determined uncertainty effects. The observed data points are evenly distributed about this line (9 above, 11 below).

The statistical analysis indicated that the difference in viewing distance (0.84 vs. 1.10 m) had no reliable effect.

## 4. Discussion

On average, thresholds rose in the uncertainty condition by a factor of 1.62, which agrees closely with the factor of 1.69 expected for the noise-driven effect which must occur even when processing limitations are absent (Greenlee & Thomas, 1993). These results argue that viewers can monitor two separate stimulus dimensions without loss of accuracy, even when two stimulus components are involved, located in different spatial frequency bands and even different spatial locations. They further suggest that when information on different dimensions is processed, any attentional restrictions in terms of locations or objects (Pashler & Johnston, 1998) may not apply. In contrast to the present results, Magnussen and Greenlee, using the same uncertainty paradigm and the same stimuli, found that thresholds rose by factors of three to six when both components were monitored for a change in a common dimension. Thus, the processing limitation observed by Magnussen and Greenlee appears to be linked to making two evaluations along a single stimulus dimension, rather than to monitoring two stimulus components, two spatial frequency bands, or two spatial locations. A like interpretation can be advanced for the results of Olzak and Wickens (1997), although they used different spatial frequencies (3 and 15 c/d) and a concurrent judgment paradigm. They found reduced accuracy when subjects made concurrent judgments about either the contrasts of both components or the spatial frequencies of both components. They did not have subjects judge the contrast of one component and the frequency of the other.

Information about contrast and spatial frequency is intermingled in the earliest cortical representation in the sense that the response of each cortical cell is jointly determined by the contrast and spatial frequency of the stimulus. Higher order operations are required to isolate one type of information from the other, and earlier research has shown that the operations required to abstract two or three different types of information can be carried out in parallel without loss of accuracy (Chua, 1990; Greenlee & Thomas, 1993; Magnussen & Greenlee, 1997; Olzak & Wickens, 1997; Vincent & Regan, 1995). The present study shows that this parallel processing occurs even when the operations address widely different stimulus components. In this context, the Magnussen and Greenlee results (Magnussen & Greenlee, 1997; Greenlee & Magnussen, 1998) mean that each type of operation loses accuracy if more than a single evaluation must be made on its dimension. The picture that emerges is of parallel mechanisms for evaluating small stimulus changes, each mechanism having as its domain a single stimulus dimension but a broader range of spatial frequencies and locations. While the mechanisms can operate in parallel without loss of accuracy, each mechanism has a limited ability to generate multiple evaluations within its domain, even when widely different stimulus components are involved.

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