Global Versus Local Processing in the Absence of Low Spatial Frequencies

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Abstract

When observers are presented with hierarchical visual stimuli that contain incongruous coarse ("global") and fine ("local") pattern attributes, the global structure interferes with local pattern processing more than local structure interferes with global pattern processing. This effect is referred to as "global precedence." The present experiments tested the hypothesis that global precedence depends on the presence of low spatial frequencies using stimuli constructed from "contrast balanced dots." Stimuli composed of contrast balanced dots are largely devoid of low-frequency content. Choice reaction time to identify either the local or global pattern information was the dependent measure. Global precedence was found only for control stimuli that contained low spatial frequencies. In the absence of low-frequency information, local precedence was obtained. These findings suggest that global precedence is heavily dependent on the low spatial frequency content of the patterns.

INTRODUCTION

The limited spatial extent of neural receptive fields in the geniculostriate pathway strongly suggests that early visual processes analyze images in a spatially discrete manner. Such discrete spatial sampling raises questions concerning the manner in which visual processes achieve a unified, holistic representation of the visual scene. Traditionally, theorists of visual pattern perception have suggested that holistic (i.e., global) pattern percepts are "constructed" via the hierarchical concatenation of lower level visual primitives or features. Indeed, the notion that higher order percepts are constructed from elementary features can be traced to the very beginnings of experimental psychology (Wundt and the early structuralists, cf. Boring 1950). A possible neural implementation of hierarchical feature processing was suggested by the early work of Hubel and Wiesel (1962), and reinforced by the discovery of higher order "perceptual units" in the temporal lobe (Gross et al. 1972).

A vast literature documents attempts to understand human visual information processing in terms of hierarchical feature processing (e.g., Biederman 1987; Geyer and DeWald 1973; Neisser 1967; Rumelhart 1970; Townsend 1971; Woldoff 1975). One relatively recent development that has received increasing attention among workers in visual perception was initiated by Navon (1977). Navon (1977) examined the relative rates of processing local patterns and more global patterns constructed from the local patterns. The actual stimuli used were large letters (the global pattern) constructed from the appropriate arrangement of smaller letters (the local pattern, see Fig. 1). Navon reasoned that if these compound letter stimuli are processed according to hierarchical feature processing, the local letters should be identified more quickly than the global letters. Reaction time (RT) to identify either the local letters or the global letter was the dependent measure. Navon (1977) found

![Figure 1](http://example.com/figure1.png)

Figure 1. An example of the type of stimulus used by Navon (1977) to study local versus global visual pattern processing. A global H made from local E's.
that, in contrast to this prediction, global RTs were faster than local RTs. Moreover, when the local letters were different from the global letter (incongruent), asymmetric interference effects were apparent. Specifically, incongruent global information interfered with local letter identification times much more than local incongruency interfered with global identification times. These asymmetric effects of local and global congruency are often interpreted as indicating the earlier availability of global information, which can then interfere with responses to the local pattern information. Both the faster identification times for letters at the global spatial scale and the asymmetric congruency effects thus appear inconsistent with hierarchical feature processing. Navon suggested that global information may actually be processed prior to local information. This pattern of results is referred to as global precedence.

Some of the subsequent work on global precedence has sought to define boundary conditions for the effect. For example, Martin (1979) showed that if the density of the local letters is reduced, global precedence is no longer obtained. Kinchla and Wolfe (1979) showed that global precedence operates only over a certain range of spatial scales; if the size of the global pattern is enlarged beyond about 9° of visual arc, then local precedence is found. Unfortunately, these workers enlarged both the local and global letters equally, so it is not clear whether the failure of global precedence in this case is due to the scale of the global letters or the scale of the local letters. Other experiments examined Navon’s hypothesis that global precedence reflects a global-to-local processing order. Thus, Miller (1981) reports redundancy gains in a target identification task when the targets were presented at both the global and local levels. This can be taken as an indication that global and local information are processed in parallel, an interpretation that is consistent with the speed-accuracy data reported by Boer and Keuss (1982). Although this work argues against a strict global-to-local processing sequence, it does not provide insights into the mechanisms that produce the relative dominance of global spatial cues in pattern processing.

Role of Low Spatial Frequencies in Global Precedence

A great deal of evidence suggests that early visual processing is mediated by mechanisms that are selectively tuned to different spatial frequencies (e.g., Kelly and Burbeck 1984; Lennie 1980; Shapley and Lennie 1985). These mechanisms appear to operate independently (at least at threshold) and in parallel (Graham and Nachmias 1971; Sachs et al. 1971; Stromeyer and Julesz 1972). Hughes et al. (1984) found evidence for strong global precedence using visual patterns in which the local and global cues were scaled to the spatial tuning characteristics of two frequency channels defined by psychophysical studies (Wilson and Bergen 1979). Based on the outcomes of these experiments, Hughes et al. (1984) suggested that global precedence might be mediated by interactions between spatial channels tuned to the global and local scales. Such interactions could confer a processing advantage to the global spatial scale. Consistent with such findings, Hughes (1986) found that response times to indicate the orientation of patterns constructed from the sum of a high (5.0 cycles deg⁻¹, cpd) and low (0.5 cpd) frequency sinewave grating showed asymmetric interference effects that favored the lower spatial frequency. In addition, Shulman et al. (1986) found that adaptation to low spatial frequencies reduced the magnitude of global precedence. Similarly, actively attending to global pattern cues enhances detectability of low frequency gratings, whereas attending to local pattern cues enhances detectability of high spatial frequencies (Shulman and Wilson 1987).

Taken together, these findings indicate that global precedence might be related to outputs of frequency-tuned mechanisms (cf. DeValois and DeValois, 1988). According to this view, global spatial structure might be directly encoded by low-frequency mechanisms rather than by hierarchical feature processing. The dominance of global over local spatial cues might be attributed to either the faster processing of low spatial frequencies (Breitmeyer 1975; Breitmeyer and Ganz 1976; Harwerth and Levi 1978) or inhibition of high-frequency mechanisms by those tuned to lower spatial frequencies (e.g., DeValois 1977; Dubin and Cleland 1977; Singer and Bedworth 1973; Tolhurst 1972). However, this view applies only to situations in which the spatial scale of the local and global pattern information corresponds with the spatial tuning of the size-specific mechanisms. Obviously, if the global cues are too large (Kinchla and Wolfe 1979), global structure must be perceived via other means.

If global precedence depends in some way on mechanisms tuned to low spatial frequencies, then removing the low-frequency content of visual patterns should reduce the dominance of the global pattern cues. This raises the problem of producing visual patterns that contain discriminative cues at both the local and global spatial scales, but that have little or no low spatial frequency content. Our solution to this problem was to construct visual patterns from a class of elements that significantly attenuates low frequencies. These pattern elements consist of small bright spots surrounded by a darker annulus. The brightness of the center spot and the darkness of the surround are chosen to produce a space-averaged luminance, which equals the luminance of the background (see Methods). Stimuli made from these elements were first investigated by Carlson et al. (1980), and are referred to as contrast-balanced (CB) dots. Stimuli constructed from contrast balanced dots provide local and global pattern information that is largely devoid of low spatial frequency content. If, as suggested above, global precedence is related to the
presence of low spatial frequencies produced by global configurations, then the degree of global precedence should be reduced when the patterns are constructed of contrast balanced elements.

Here we report the results of two experiments that test this prediction. Since the design of the stimuli represents an essential aspect of these experiments, we now present a brief description of patterns.

**Stimulus Design**

The basic element used to construct the patterns in both experiments was a small dot. The experimental dots were contrast balanced; they consisted of a bright center region and a darker surround, with the space averaged luminance of the bright and dark regions equal to the background luminance. The details of the contrast balancing procedure are described in the Methods section. Bright and dark control dots were created by displaying only the bright center or dark surround of the contrast balanced dots. All stimulus patterns were constructed from either the contrast balanced or the control dots.

For the first experiment, dots were assembled into horizontal or vertical line segments. Horizontal and vertical clusters were assembled from 10 of these lines. There were 4 classes of clusters: horizontal clusters built from horizontal line segments, vertical clusters built from vertical line segments, horizontal clusters built from vertical line segments, and vertical clusters built from horizontal line segments (see Fig. 2A-C for sample patterns). The first two types of clusters formed the congruent patterns and two second two types formed the incongruent patterns. Libraries of these clusters were created for the contrast balanced and bright and dark control stimuli.

In the second experiment, contrast balanced and control dots were used to construct small squares and diamonds. Larger squares and diamonds, which formed the global stimuli, were constructed from these small figures (see Fig. 2D–F for examples). The congruent stimuli were either large squares formed from small squares or large diamonds formed from small diamonds. Incongruent stimuli were either large squares made of small diamonds or large diamonds made of small squares.

The attenuation of low spatial frequencies in the experimental patterns, relative to the control patterns, can be confirmed qualitatively by simply viewing the displays at a relatively long distance. Since the contrast-balanced stimuli contain primarily high spatial frequencies and the spatial frequencies in any image increase in direct proportion to the viewing distance, the experimental patterns "disappear" at longer viewing distances since their component frequencies surpass the sensitivity range of the human visual system. In contrast, since the control patterns contain low-frequency information, they remain visible at viewing distances which render contrast-balanced displays invisible (see Fig. 2).

A more formal illustration of the frequency content in examples of the experimental and control patterns is shown by the power spectra in Figure 3. These two-dimensional Fourier transforms are represented in polar coordinates, so each combination of spatial frequency and orientation is represented as a vector. Spatial frequency is represented by the magnitude of the vector (i.e., the distance from center of each figure) and the orientation is represented as the angular direction. Amplitude is color coded, with the lowest amplitudes shown as black and the highest as violet. Low spatial frequencies lie near the origin, so the conspicuous dark central area in the transform of the contrast-balanced pattern signifies an absence of low-frequency content. It can be seen that contrast balancing removed almost all of the power below about 3.0 cpd. The control patterns obviously contain a great deal of power at these same frequencies. Since the experimental and control patterns differ primarily in their low-frequency content, performance differences produced by these patterns are likely due to the presence or absence of low-frequency information.

**EXPERIMENT 1**

**Results and Discussion**

**Data Analysis**

As indicated in the introduction, experiments on global precedence often find both an overall RT advantage for global forms over local forms in addition to asymmetric congruency effects in which local processing is more susceptible to interference. However, asymmetric congruency effects that favor global responding can occur in the absence of any differences in RTs to the global or local cues (e.g., Hughes et al. 1984; Hughes 1986; Lamb and Robertson 1989). Indeed, it has been argued that faster responses to the global level could indicate a relatively greater discriminability of the global as opposed to local cues. In this case, global precedence could simply be the reflection of differences in visibility of the cues. The fact that asymmetric congruency effects can occur when the raw RTs are equated (e.g., Hughes 1986) provides strong evidence that global precedence is not merely a reflection of discriminability. As congruency effects appear to be a more reliable and robust measure of the relative dominance of local versus global processing, the present results are described primarily in these terms.

**Accuracy Analysis**

Error rates were first transformed (arc sine) and then submitted to an analysis of variance with target condition (local versus global), display type (balanced versus unbalanced), and congruency as factors. This analysis indicated a main effect of congruency (error rates were significantly greater for responses to incongruent pat-
Figure 2. Samples of incongruous stimuli used in Experiment 1 (A,B,C) and Experiment 2 (D,E,F). As the viewing distance is increased, the contrast balanced patterns should disappear, but the control patterns remain visible. See text for details. However, because of limitations in the reproduction of the original gray levels, the contrast balancing may not be perfect. Fourier transforms of these patterns are illustrated in Figure 3.
Figure 3. Fourier transforms of the representative stimuli shown in Figure 2. Transforms on the left are of a horizontal cluster of vertical lines (see Fig. 2A–C); transforms on the right are of a global diamond made of local squares (see Fig. 2D–F). (A) and (D) were constructed from contrast balanced dots. (B) and (E) are the bright control patterns and (C) and (F) are the control patterns made from the dark surround. Lower frequencies are represented toward the center of the transforms. The inner and outer circles shown in (A) and (D) encompass frequencies below 3.0 and 6.0 cycles deg$^{-1}$ (cpd), respectively. Power is color coded on a $\log_{10}$ scale: black, blue, cyan, green, yellow, orange, red, and violet represent increasing power. Note the relative absence of power below 3.0 cpd in the contrast balanced figures (A and D).
tions, $F(1,11) = 106.9, p < .001$] and a three-way interaction between target condition, display type and congruency [$F(1,11) = 15.9, p < .002$]. Analysis of the means contributing to this interaction indicated that higher error rates were consistently associated with slower response times. There was therefore no indication that the latency data were confounded by a speed-accuracy trade-off.

Latency Analysis

The raw RT data obtained in both experiments are presented in Table 1, and analyses are presented below. Separate analyses of the two types of control pattern (bright dots versus dark annuli) indicated no differences between these displays, so these data were pooled in all subsequent analyses. There were no differences in global versus local RTs in Experiment 1, but there was in Experiment 2. In both experiments however, the magnitude of local-global incongruency effects varied with the spectral content of the patterns in a consistent manner.

The congruency effects (i.e., the RT difference between congruent and incongruent displays) are shown in Figure 4. When the patterns contained low spatial frequencies, the magnitude of local interference on global response times was 27 msec, but the magnitude of global interference on local response times was 47 msec. These asymmetric interference effects are characteristic of global precedence. This pattern of interference is reversed, however, when the low spatial frequencies were removed. As indicated in the left half of Figure 4, contrast balancing produced more local-on-global interference (47 msec) than the converse (13 msec). Contrast balancing therefore produced a pattern characteristic of local precedence.

This conclusion was confirmed statistically by an ANOVA of the congruency scores, which revealed a significant interaction between target condition (local versus global) and display type (balanced versus unbalanced), $F(1,11) = 54.6, p < .001$. Paired comparisons indicated that control patterns (containing low spatial frequencies) produced significantly more global-on-local than local-on-global interference. The opposite pattern was obtained for the contrast-balanced displays.

A three-way ANOVA was also performed on the raw RTs (see Table 1), and further demonstrated the reversal of global precedence with contrast-balancing. There were significant main effects of congruency [$F(1,11) = 114.55, p < .001$] and contrast balancing [$F(1,11) = 48.06, p < .001$], but no main effect of global versus local targets ($F < 1$). There was a significant two-way interaction between contrast balancing and global versus local targets [$F(1,11) = 8.52, p < .02$] and a triple interaction [$F(1,11) = 53.69, p < .001$]. Post hoc comparisons (Newman–Keuls procedure) between the means contributing to this triple interaction indicated the following. First, congruency produced faster choice RTs than incongruency for both contrast-balanced and control patterns. Congruence effects were also apparent for both local and global judgments. However, the magnitude of this interference varies with both the spatial scale of the target (local or global) and the presence of low spatial frequencies (contrast balancing), in a manner consistent with global precedence when the patterns contain low-frequency information, but local precedence when they do not.

Before accepting this conclusion, however, we address a possible confounding factor in these results. Since both the local and global cues in these patterns were randomly distributed over an area of 144 deg$^2$ of visual arc, the average eccentricity of the global cues tends to be greater than the nearest local elements. As the contrast-balanced elements contain only high-frequency information, they would tend to be less visible in the periphery than in central vision. This could confer a relative advantage to local processing with the contrast-balanced patterns. The fact that the overall RTs for both local and global cues were not significantly different with contrast-balanced patterns argues against this possibility. We nevertheless decided to examine the issue using stimuli that controlled for the eccentricity of both the local and global cues. This was done using stimuli that formed a global outline of a square or a diamond. The global forms were constructed from the appropriate spatial arrangement of smaller squares or diamonds, which in turn were con-

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<th>Table 1. Mean Reaction Times and Standard Deviations for Experiment 1 and Experiment 2</th>
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structured of either contrast-balanced or unbalanced dots (see Fig. 2). The global forms were centered around the fixation point, so that the eccentricity of both the global and local cues was constant (~ 2.2°).

EXPERIMENT 2

Results

The results of this experiment replicate the basic finding of Experiment 1. The congruency effects illustrated in Figure 5 indicate global precedence for the control patterns and local precedence for contrast-balanced displays.

An ANOVA on these congruency scores, revealed a significant main effect of contrast balancing \(F(1,11) = 8.46, p < .02\) and a significant interaction between contrast balancing and the spatial scale of the target \(F(1,11) = 12.94, p < .004\). As in the first experiment, paired comparisons indicated that control displays produced more global-on-local than local-on-global interference \(t(11) = 3.2, p < .005\), whereas the opposite pattern was obtained for contrast-balanced displays \(t(11) = 1.85; p < .05; \text{one-tailed}\).

The latency data (Table 1) were further analyzed in a three-way ANOVA with congruency, contrast balancing, and target spatial scale as factors. There were significant main effects of congruency \(F(1,11) = 64.56, p < .001\) and contrast balancing \(F(1,11) = 62.94, p < .001\), and
global versus local targets \(F(1,11) = 11.28, p < .01\). In addition, there was a significant two-way interaction between contrast balancing and congruency \(F(1,11) = 8.46, p < .02\). The triple interaction between congruency, contrast balancing, and global versus local targets was also significant \(F(1,11) = 13.02, p < .01\). Post hoc comparisons (Newman–Keuls procedure; \(p < .05\)) indicated significant congruency effects for all relevant comparisons (local and global targets, with and without low spatial frequencies). As in the first experiment, this analysis indicated that global precedence was evident only for the displays containing low spatial frequencies. Contrast balancing produced more local-on-global interference than global-on-local interference, that is, local precedence.

**GENERAL DISCUSSION**

The results of both experiments indicate that, at least under these experimental conditions, global precedence was closely related to the low-frequency content of the stimuli. In the absence of low spatial frequencies, evidence for local precedence was obtained. These results are consistent with the view that global information can be directly encoded by low-frequency channels. Under these circumstances, global cues appear to dominate visual pattern processing. In contrast, when the patterns are devoid of low-frequency content, global pattern structure presumably must be "constructed" from the local features. This situation appears to favor local pattern processing.

Several previous manipulations that influenced the magnitude of global precedence might also be understood in terms of the spatial frequency content of the stimuli. The transition from global to local precedence that accompanies increasing pattern size might be attributed to an overall lowering of the frequency components in the power spectra as the patterns are increased in size. At a sufficiently large scale, the frequency components carrying the global information might be so low that they exceed the tuning characteristics of the low-frequency mechanisms (Wilson and Bergen 1979). In this case, global pattern information could not be directly encoded by these low-frequency channels, and presumably must be obtained through other means. Reports indicating that global precedence is diminished with reductions in the high-frequency components of the temporal power spectra of the patterns (Hughes 1986; Paquet and Merikle 1984) can be attributed to the well-established transient response characteristics of low-frequency mechanisms (Burbeck and Kelly 1981; Kelly and Burbeck 1984; Lehmkühle et al. 1980; Tolhurst 1975). Evidence that global and local information is processed in parallel (although not necessarily at the same rate; Miller 1981; Boer and Keuss 1982) is compatible with the view that local and global pattern attributes can be encoded by spatial frequency mechanisms which themselves appear to operate in parallel. Finally, evidence indicating that global precedence is eliminated by reductions in the density of the local pattern elements (Martin 1979) could be accounted for in terms of reduced ability to encode the global form on the basis of low frequency information. As indicated in Figure 6, low density global forms are not well represented by low spatial frequencies, and must presumably be assembled hierarchically by grouping processes.

It is important to acknowledge however, that not all of the empirical findings on the global precedence effect can be explained in terms of the characteristics of the visual images used. For example, Paquet and Merikle (1988) report evidence that global precedence is at least partially under strategic control of endogenous attentional influences. However, since there is evidence that human observers can selectively attend to specific bands of spatial frequencies (Davis 1981), demonstrations of such attentional influences do not necessarily argue against the hypothesis that low level spatial filters play an important role in mediating global precedence effects.

It is obvious, however, that removal of low spatial frequencies does not abolish global pattern percepts, since observers clearly respond to global cues in patterns devoid of low-frequency content. In this situation, global percepts must clearly be achieved through some other means, such as hierarchical processing. What these data indicate, however, is that in the absence of low frequencies, global information no longer dominates local pattern processing.

**METHODS**

**Stimuli**

Patterns were generated on a Macintosh II computer and displayed on a Macintosh monochrome monitor. Subjects viewed the stimuli binocularly at a distance of 57 cm. The background luminance of the screen was set to 19 cd/m², at the midpoint of the computer’s 256-step gray scale range. Contrast-balanced dots consisted of a bright center region 2 × 2 pixels square and a 1 pixel wide dark surround. At a viewing distance of 57 cm, each pixel subtended 2 arc/min, so the width and height of the dots was 8 arc/min. Dots were “rounded” by removing the corner pixels from the dark surround, producing a 2:1 ratio of dark to bright pixels in each dot.

To achieve contrast balancing, we initially set the luminance of the dark pixels 18 cd/m² lower than the background and the bright pixels 36 cd/m² above the background. However, when we displayed a patch of balanced dots, the patch remained visible as a dim area when viewed at a distance that rendered the individual dots invisible. We therefore slightly increased the luminance of the bright pixels so that the screen appeared a uniform gray when viewed from a distance. The actual luminances employed after this adjustment were 1 cd/
m² for the dark pixels and 58 cd/m² for the bright pixels. Bright and dark control dots were created by displaying only the bright center or dark flanks of the contrast balanced dots.

In the first experiment, dots were assembled into horizontal or vertical line segments, one dot wide and four dots long; these segments had a width of 8 arc/min and a length of 44 arc/min (0.13° × 0.73°). The clusters were assembled from 10 of these lines. Each cluster had a maximum width of 1.2° and a maximum length of 5°. The placement of the lines within each cluster was random, with the constraint the lines did not overlap or touch. Each pattern consisted of a randomly selected set of seven clusters, randomly arranged within the central 12 × 12° of the monitor screen. The only constraint was that the clusters did not overlap or touch.

In the second experiment each side of the local squares or diamonds consisted of three dots and subtended 32 arc/min (0.53°). The global squares and diamonds were constructed from these small figures. Each side of the large figures consisted of three of the smaller figures, and subtended 212 arc/min (3.53°). On each trial, the display consisted of a single global figure centered around the fixation point.
Subjects were seated in front of the computer monitor with their head positioned by a chin cup. They were given a two key response box, and placed the index finger of each hand on one of the keys. On different experimental runs, the global or local elements were designated as the targets. A small fixation cross remained continuously present on the CRT screen. On each trial, a brief warning tone sounded (500 Hz for 0.1 sec) followed after a 0.5 sec delay by a 204 msec presentation of the stimulus display. In Experiment 1, subjects were instructed to press the left button if the orientation of the stimuli (at the designated level) was vertical and the right button if the orientation was horizontal. In Experiment 2, they pressed one button if the figure (at the designated level) was a square and the other if it was a diamond. Subjects were instructed to respond as quickly as possible. An experimental run consisted of 120 trials: 40 trials with contrast balanced stimuli, 40 with the bright control stimuli, and 40 with the dark control stimuli. Trials occurred at a rate of one every 3.0 sec. The global and local levels were congruent for half the presentations and incongruent for the other half. The order of the stimulus presentations was randomized within each set of 120 trials. Eight experimental runs were conducted with each subject, four with local targets and four with global targets. Global and local runs were counterbalanced using an ABBAABBA scheme. Prior to formal data collection, two practice runs (one global and one local) were conducted. A MacPacq A/D system (Biopac Systems) was used to monitor the response buttons, and recorded subject’s response latency to the nearest millisecond.

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