

An ERP study of the global precedence effect: the role of spatial frequency

Shihui Han^{a,*}, E. William Yund^b, David L. Woods^b

^aDepartment of Psychology, Center for Brain and Cognitive Sciences, Peking University, 5 Yiheyuan Road, Beijing 100871, PR China

^bDepartment of Neurology, University of California at Davis, VA Northern California Health Care System, 150 Muir Road, Martinez, CA 94553, USA

Accepted 27 May 2003

Abstract

Objective: This study investigated the neural mechanisms underlying the effects of removal of low spatial frequency (SF) contents from stimulus displays on the processing of global and local properties of compound stimuli.

Methods: Event-related brain potentials (ERPs) were recorded from 16 subjects who selectively attended to the global or local features of compound letters, which were either white on a gray background containing broadband SFs or were contrast-balanced (CB) to eliminate low SFs, and were randomly presented in the left or right visual fields. ERPs were analyzed to examine how global/local attention modulations of neural substrates were influenced by SF manipulations.

Results: We found that an early process of global recognition was indexed by a negativity peaking at 190 ms over contralateral occipito-temporal cortex and was eliminated by contrast balancing. The late stage of global recognition was reflected in a late negativity peaking at 300 ms and was only retarded by contrast balancing. Global-to-local interference was characterized by enhanced occipito-temporal negativities and was evident for both broadband and CB stimuli.

Conclusions: The results clarify distinct cognitive and neural mechanisms underlying the global precedence and interference effects, which were different in terms of the independence of low SFs in compound stimuli.

© 2003 International Federation of Clinical Neurophysiology. Published by Elsevier Ireland Ltd. All rights reserved.

Keywords: Compound stimuli; Contrast balancing; Event-related potentials; Global/local processing; Spatial frequency

1. Introduction

Human observers can perceive properties at multiple levels of hierarchical visual scenes, but the mechanisms whereby human viewers process the global configurations and the composing parts remain poorly understood. This problem has been studied extensively since Navon's (1977) pioneering work. The typical stimuli used in these studies are global letters or shapes consisting of local letters or shapes, as those illustrated in Fig. 1a. Navon showed that reaction times (RTs) to identify local targets were slower than those to global targets (global RT advantage) and local RTs were delayed by incongruent global shapes (global-to-local interference). In contrast, responses to global targets were not affected by local shapes. Based on these results, Navon proposed that global information is coded first

whereas local information is analyzed at a later stage of visual perception, i.e. the global precedence hypothesis.

Mechanisms at different levels of processing have been proposed to interpret the global precedence effect. For example, since global structures are usually larger than local parts, the global precedence may simply reflect the difference in discriminability between global and local shapes of compound stimuli (Grice et al., 1983; Pomerantz, 1983; but see Hughes et al., 1984). Alternatively, the difference between global and local processing may result from the intrinsic properties of the transient and sustained visual systems that are most sensitive to low and high spatial frequencies (SFs) and carry global and local information, respectively (Ward, 1982). Visual attention may also contribute to the global precedence effect. Large attentional window produced by abrupt visual onset covers global shapes first and takes time to focus on local shapes (Robertson et al., 1993; Stöffer, 1994). Strong grouping of local elements into global configurations competes with selection of an individual local element from global structures and produces faster responses to global than

* Corresponding author. Tel.: +86-10-6275-9138; fax: +86-10-6276-1081.

E-mail address: shan@pku.edu.cn (S. Han).

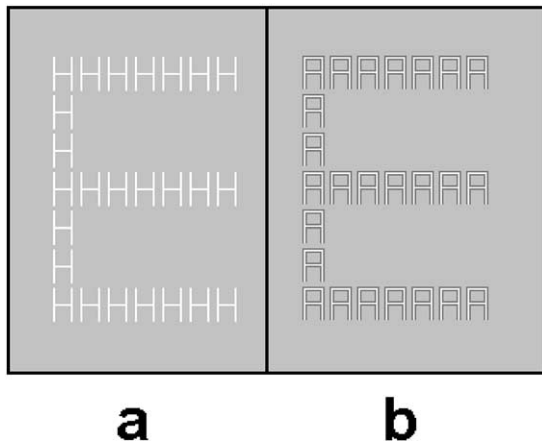


Fig. 1. Illustrations of the compound stimuli used in the current study. (a) A broadband global E made up of local H and (b) a contrast-balanced global E made up of local A.

local targets (Han and Humphreys, 1999, 2002; Han et al., 1999b).

Among these hypotheses, the role of SF information in the global precedence effect has been studied extensively. Shulman et al. (1986) first demonstrated a close relationship between global/local processing and low/high SF channels. They measured RTs to global and local targets after adaptation to sine-wave gratings of low and high SFs. They found that the adapting frequency that most disrupted the global task was lower than that most affecting the local task. Shulman and Wilson (1987) showed further that low SF gratings were more easily detected than high SF gratings when subjects were involved in a primary task of identifying global forms of compound stimuli. In contrast, high SF gratings were more easily detected during identification of local forms. These results suggest that low SF channels play a key role in mediating information at the global level of compound stimuli whereas high SF channels are important in carrying information at the local level.

Other researchers have directly manipulated the SF contents of compound stimuli. The rationale is that, if the global precedence reflects faster response and shorter integration time of low relative to high SF channels, removing low SF contents from compound stimuli should eliminate the global RT advantage. In addition, if global-to-local interference stems from inhibition of high SF channels by low SF channels, removing low SFs from stimuli should also weaken global-to-local interference. One method to test these hypotheses is to use high-pass-filtered stimuli, which are generated by weighting the spectrum of compound stimuli with a high-pass filter and transforming the results back to the spatial domain. Several studies indeed found that high-pass spatial filtering eliminates the global RT advantage (Badcock et al., 1990; Lagasse, 1993).

'Contrast-balanced' (CB) stimuli provide an alternative to high-pass filtering, in eliminating low SFs from compound stimuli (Hughes et al., 1990; Lamb and Yund,

1993, 1996a,b, 2000; Lamb et al., 1999; Robertson, 1996). CB stimuli consist of bright bars (or dots) surrounded by dark bars (or dots) to construct local letters that are presented on a gray background. The luminance levels of the brighter and darker areas are arranged such that the space-averaged luminance of any short segment of bright and surrounding dark bars (or dot clusters) within the CB stimuli is equivalent to that of the background. This method of construction eliminates all long-distance space-averaged luminance differences and thus produces stimuli without low SFs (Hughes et al., 1990; Lamb and Yund, 1993, 1996a,b). As a result, both global and local shapes in the compound stimuli must be identified exclusively with information transmitted by the high SF channels. Hughes et al. (1990) showed that removing low SF by contrast balancing reduced global-to-local interference and increased local-to-global interference. Lamb and Yund (1993, 1996a,b) found that the global RT advantage observed for broadband stimuli was eliminated by contrast balancing the stimuli regardless of whether the stimuli were presented in the center or periphery of the visual field. However, the interference between global and local forms was little affected by contrast balancing. They argued that, while faster responses of low SF channels may be the substrate of the global RT advantage, interference between global and local forms are not based on SFs.

Although the aforementioned studies demonstrate that some aspects of the processing of compound stimuli is sensitive to the presence of low SFs, the cognitive and neural mechanisms underlying the role of low SF in the global RT advantage and global-to-local interference are still unclear. For instance, in what aspect is the global perception different between broadband and CB compound stimuli given that low SFs are not available in CB stimuli? This critical issue has not been resolved although RT results suggest that removing low SFs from compound stimuli slows the global perception. In addition, what are the neural mechanisms that underlie the elimination of global precedence by contrast balancing? One possibility is that removing low SFs from compound stimuli simply delays the processing of global properties at all stages. Alternatively, removing low SFs from compound stimuli may weaken some early components of global processing based on low SFs. Behavioral studies cannot clarify the above issue because RT measurement indicates the final output of processes including sensory, perceptual processing, and response selection and execution.

Moreover, while the behavioral data showed global-to-local interference for both broadband and CB stimuli (Lamb and Yund, 1993, 1996a,b), it is unknown whether the neural mechanisms underlying the interference effects are similar for the two sets of stimuli. The fact that global-to-local interference exists for both broadband and CB stimuli does not necessarily mean that the same mechanism underlie the interference between global and local processing under the conditions when SFs are or are not available in stimulus

displays. The results of previous behavioral studies are unable to solve this problem. However, to understand this question is important for building any computational models of global/local processing based on SF analysis.

The current experiment sought to investigate these issues with event-related brain potential (ERP) recordings. ERPs arise from the synchronous activities of neuronal populations engaged in specific processing and are time locked to stimulus events. High time resolution makes ERPs useful in revealing the time course of specific neural activation. The scalp distribution of ERPs also provides information about the location of activated brain areas. ERPs have been used in a number of studies to examine neural mechanisms underlying global/local processing of compound stimuli. For instance, [Heinze and Münte \(1993\)](#) had subjects respond to targets at either the global or local levels of compound letters presented in the center of the visual field (a divided attention procedure). They found that a posterior negative wave (N2 with peak latency between 200 and 300 ms), with maximal amplitudes at occipito-temporal areas, showed larger amplitudes to local than to global targets. Similar results were reported in studies using compound shapes ([Han et al., 2000a,b](#)). Modulations of ERPs by global/local processing were also evident in studies using a selective attention procedure. For example, [Han et al. \(1997\)](#) had subjects identify either global or local shapes in the center of the visual field in separate blocks of trials. They found an enhanced occipito-temporal N2 in the local relative to global conditions. Similar modulations of the posterior N2 were observed during selective attention to global or local features of compound stimuli displayed in the periphery of the visual field ([Han et al., 1999a, 2000b](#)). The ERP components over the anterior areas are also modulated by global/local processing ([Han et al., 1997](#)): local targets elicited anterior N2 and P3 waves with longer peak latencies relative to global targets when behavioral data showed a global RT advantage.

ERPs are also modulated by the congruency between global and local shapes. [Han et al. \(Han and Chen, 1996; Han et al., 1997\)](#) found that the posterior N2 was larger when global and local shapes were incongruent relative to when they were congruent. The latencies of the anterior N2 and parietal P3 were also delayed by the incongruency between global and local shapes. [Proverbio et al. \(1998\)](#) observed shorter latency effects with peripheral presentation of stimuli: a reduced occipital N1 in the local task when global configurations were inconsistent with local shapes. Taken together, the ERP findings suggest multiple-level neural substrates underpin differential global/local processing and the interaction between them. However, as all the ERP studies used broadband compound stimuli, it is unclear how the neural mechanisms underlying global and local processing are influenced by low SFs in compound stimuli.

In the present study, we recorded ERPs from subjects while they responded to global or local levels of compound letters that appeared randomly in the left visual field (LVF)

or the right visual field (RVF). Letters ‘H’ and ‘S’ served as targets while ‘A’ and ‘E’ served as distractors, as illustrated in [Fig. 1](#). Two sets of stimuli were used. The first set was composed of local letters that were white on a gray background. These stimuli contain a broad band of SFs (broadband stimuli). The second set of stimuli was the same as the broadband stimuli except that they were contrast-balanced to eliminate low SFs (CB stimuli). We first compared ERPs related to global and local processing of broadband and CB stimuli to examine how differential global/local processing is affected by the presence of low SFs. The role of SFs in cognitive process of global/local target perception was examined by comparing target specific difference waves, which were obtained by subtracting ERPs to nontarget stimuli from those to target stimuli and thus eliminate effects of low-level sensory processing. If removing low SFs simply postpones global processing, contrast balancing should only delay the peak latencies of the components of ERPs and target difference waves in the global task. Otherwise, any waveform changes (particularly the changes of early components of ERPs or target difference waves) resulting from contrast balancing would suggest existence of specific processes involved in global perception based on low SFs.

The mechanisms of the interference effect were investigated by comparing ERPs to targets that were composed of distractors with shapes similar or dissimilar to targets. ‘A’ is more similar to ‘H’ relative to ‘E’, and ‘E’ is more similar to ‘S’ relative to ‘A’. Dissimilar distractors may operate like incompatible targets and slowed responses to targets ([Lamb and Robertson, 1989; Lamb and Yund, 1993](#)). If the interference is observed in behavioral responses to both broadband and CB stimuli, the ERP signs of interference should help to reveal whether the same brain areas mediate the interference with similar time course for both broadband and CB stimuli.

Finally, the relationship between SF analysis and hemispheric asymmetry in global/local processing was explored by comparing the effects of contrast balancing on ERPs to LVF and RVF stimuli. Neuropsychological studies found that left hemisphere lesions impair the processing of local aspects of compound stimuli whereas right hemisphere lesions result in deficits in global processing ([Delis et al., 1986; Lamb et al., 1989, 1990; Robertson et al., 1988, 1993](#)), indicating that the right and left hemispheres dominate global and local processing, respectively. Given the hypothesis that, at some level of processing, the left and right hemispheres are biased toward efficient use of higher and lower SF information, respectively ([Christman et al., 1997; Kitterle and Selig, 1991; Ward, 1982](#)), some researchers suggest that the lateralized global/local processing is mediated by hemispheric specialization for the analysis of SFs ([Sergent, 1982; Shulman et al., 1986](#); see [Ivry and Robertson, 1998](#) for review). If the right hemisphere dominates processing of low SFs that mediate global perception, then removing low SFs should produce larger

effects on global processing when stimuli are presented in the LVF than in the RVF. In contrast, insofar as local processing is mediated by high SF channels, the effects of removing low SF on local perception should not differ between the LVF and RVF stimuli.

2. Methods

2.1. Subjects

Sixteen young adults (9 men, 7 women; aged between 19 and 37 years) participated as paid volunteers. All had normal or corrected-to-normal vision. All participants were right-handed, without neurological disorders, and gave informed consent according to the guidelines of the Veterans Administration Medical Center and the University of California, Davis.

2.2. Stimuli

The stimuli were global letters made up of local letters in a 7×7 matrix, as illustrated in Fig. 1. Letters 'H' and 'S' served as targets while Letters 'A' and 'E' served as distractors. Each stimulus pattern either contained one target at the global level (i.e. global/local: H/A, S/A, H/E, or S/E) or at the local level (i.e. A/H, E/H, A/S, or E/S), or contained no targets (i.e. A/E or E/A), resulting in 10 stimulus figures. The shapes at global and local levels were either similar (i.e. H/A, S/E, A/H, or E/S) or dissimilar (i.e. H/E, S/A, E/H, or A/S). At the viewing distance of 130 cm, global letters were 2.8° wide and 4.2° high. Local letters were 0.27° wide and 0.48° high.

Stimuli were presented on a gray (17.0 cd/m^2) background. Each local letter of the broadband stimuli was composed of lines that were brighter (31.6 cd/m^2) than the background (see Fig. 1a). The CB stimuli were identical to the broadband stimuli except that the bright lines composing each local letter were surrounded by lines that were darker (10.5 cd/m^2) than the background. The change in luminance from background was approximately twice as great for bright lines as for dark lines (see Fig. 1b). Because dark lines occupied twice as much area as bright ones, the space-averaged luminance of the CB stimuli equaled that of the background. The arrangement of the luminance levels of the brighter and darker areas comprising the local letters and the gray background removed spectral power below 3 cycles/degree from the CB stimuli (see Lamb et al., 1999 for the result of spectral power analysis). All line segments comprising the local letters (both bright and dark) were approximately 0.015° thick.

A fixation cross of $0.2^\circ \times 0.2^\circ$ was continuously visible in the center of the monitor. The compound stimuli were displayed to the left or right of the fixation. The distance between the fixation and inner edge of the compound stimulus was 1.2° . The stimulus displays were presented for

200 ms. Interstimulus intervals (ISIs) were randomized between 500 and 1000 ms.

2.3. Procedure

A selective attention paradigm was used. Each block of trials contained 16 alternating 20 s sections. At the beginning of each section, a large or a small letter made up of solid black lines was presented for 1000 ms to direct subjects' attention to the global or local level of the forthcoming compound stimuli. The sizes of global and local cues were the same as those of global and local letters of the compound stimuli. Subjects responded with a button press to targets. There were 25 trials in each section (target probability = 20%). After 100 practice trials, 6 blocks (each containing 400 trials) were presented for broadband and CB stimuli, respectively. The broadband and CB stimuli were presented in alternate blocks of trials. The order of conditions and hand of response were counterbalanced across subjects.

2.4. ERP data recording and analysis

The electroencephalogram (EEG) was continuously recorded from 60 scalp electrodes. The electrodes were located according to the International 10–20 system. Additional electrodes were located at non-standard intermediate locations (see Fig. 2). The right earlobe was used as reference. Eye blinks were monitored with electrodes located below the left eye. The horizontal electro-oculogram was

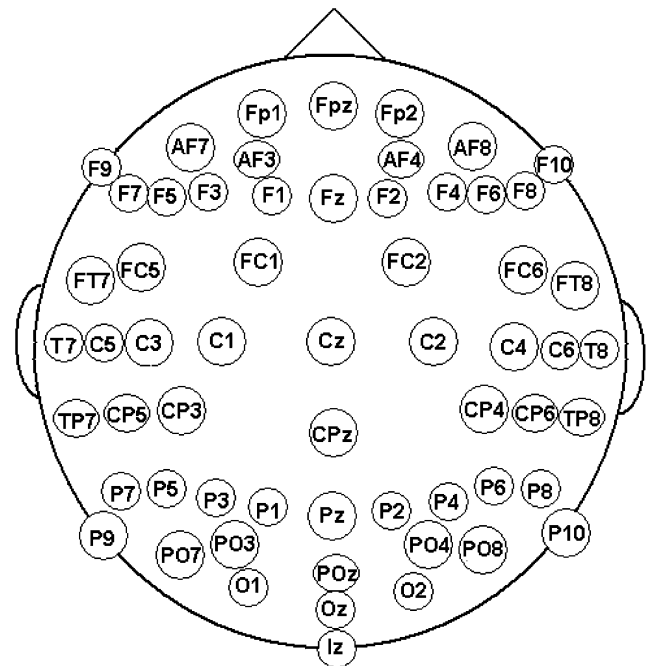


Fig. 2. Illustration of the top view of spherical projections of the 60 electrodes used in the current study.

recorded from electrodes placed 1.5 cm lateral to the left and right external canthi (i.e. F9, F10). The EEG was amplified with a half-amplitude band pass of 0.01–80 Hz and continuously digitized on-line at a sampling rate of 256 Hz. The ERPs to each type of stimuli were averaged separately off-line with averaging epochs beginning 200 ms before stimulus onset and continuing for 1000 ms. For target stimuli, only trials with correct responses were analyzed. For nontarget stimuli, only trials not followed by responses were analyzed. Trials contaminated by eye blinks, eye movements, amplifier clipping, or muscle potentials exceeding 160 μv (peak-to-peak amplitude) at any electrode were excluded from the average, resulting in exclusion of about 5–10% trials from average. Peak latencies were measured relative to stimulus onset. Mean voltage of ERPs were obtained (a) at 20 ms intervals starting at 60 ms after stimulus onset and continuing until 300 ms post-stimulus and (b) at 40 ms intervals from 300 to 700 ms post-stimulus. Because CB stimuli elicited ERPs with peak latencies significantly delayed relative to broadband stimuli, peak amplitudes were measured to examine the effect of contrast balancing. Table 1 shows time windows of the measurements of each ERP component. Statistical analysis was restricted to a small set of electrodes (F3–F4, C3–C4, P3–P4, O1–O2, PO3–PO4, PO7–PO8, and P9–P10) where the ERP waves of interests showed large amplitudes. Because preliminary analyses showed that most of the effects were evident over the lateral occipital regions, we selected more electrodes over the lateral occipital areas than the frontal–central areas for the statistical analysis.

RTs and hits were subjected to a repeated measure analysis of variance (ANOVA) with Frequency Content (broadband or CB stimuli), Level of Attention (global or local), Hemifield (the LVF or the RVF), and Distractor Letter (distractor letters were similar or dissimilar to target letters) as independent variables. False alarm rates were subjected to ANOVAs with factors being Frequency Content, Level of Attention, and Hemifield. The mean and peak amplitudes and peak latencies of ERPs to target stimuli were subjected to ANOVAs over each pair of electrodes (e.g. F3–F4 and PO7–PO8) with Frequency Content, Level of Attention, Hemifield, Distractor Letter, and Hemisphere (electrodes over the left or the right hemispheres) as independent variables. The mean and peak amplitudes and peak latencies of ERPs to nontarget stimuli were subjected

to ANOVAs with Frequency Content, Level of Attention, Hemifield, and Hemisphere as independent variables. Statistical comparisons of scalp distributions were performed on normalized amplitudes with Greenhouse–Geisser correction. The onset of target difference waves were identified by comparing the ERPs to targets and nontargets. The time point at which ERPs to target and nontargets started to differ significantly was defined as the onset of target difference waves (this is the same as that the difference wave was significantly different from zero).

3. Results

3.1. Behavioral performance

3.1.1. RTs

RTs to broadband and CB targets are shown in Fig. 3. Overall, subjects responded faster to broadband than CB stimuli (476 vs. 537 ms, $F(1, 15) = 260.9$, $p < 0.001$), and this effect was significant for global as well as local tasks ($F(1, 15) = 159.7$ and 143.8, respectively, both $p < 0.001$). On average, subjects responded faster to targets in the RVF than in the LVF ($F(1, 15) = 13.2$, $p < 0.003$).

There was a significant interaction of Frequency Content \times Level of Attention ($F(1, 15) = 27.8$, $p < 0.001$). Post hoc analyses revealed shorter RTs to global relative to local targets for broadband stimuli ($F(1, 15) = 20.9$, $p < 0.001$), whereas no difference was found between global and local responses for CB stimuli ($F(1, 15) = 1.86$, $p > 0.1$). The results indicate that contrast balancing slowed responses to targets to a greater extent in the global than local

Table 1
Time windows of measurements of peak amplitudes

	Broadband	CB
P1	100–200	120–220
N1	150–250	200–300
Posterior N2	300–400	300–400
Anterior N2	300–400	300–400
P3	350–700	350–700

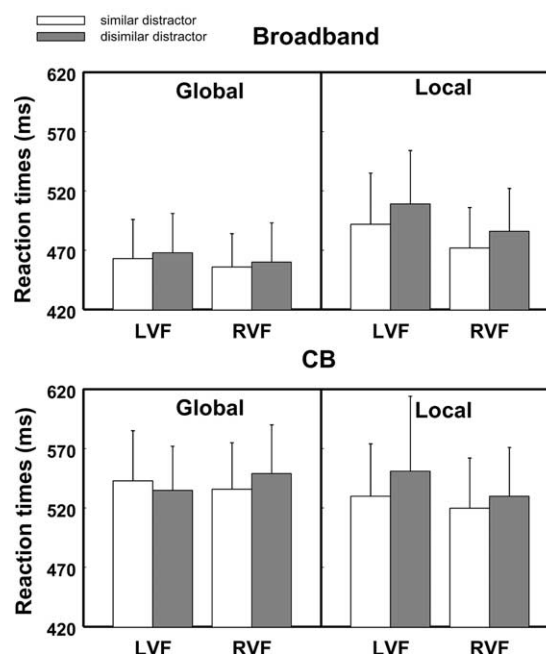


Fig. 3. Results of RTs in each condition for broadband and CB stimuli.

conditions, consistent with previous reports (Badcock et al., 1990; Lamb and Yund, 1996a,b). Consequently, global/local responses to CB stimuli became equally fast. This is in agreement with the claim that the global precedence is mediated by rapidly conducting channels sensitive to low SFs. There was a significant interaction of Level of Attention \times Hemifield ($F(1, 15) = 6.71$, $p < 0.02$) for broadband stimuli, due to that the global RT advantage was larger in the LVF than in the RVF. For CB stimuli, however, there was a local RT advantage for the RVF stimuli but no difference between global and local RTs for the LVF stimuli, resulting in a significant interaction of Level of Attention \times Hemifield ($F(1, 15) = 9.96$, $p < 0.007$).

RTs were faster when distractors at unattended levels were similar to targets relative to when distractors were dissimilar to targets for both broadband and CB stimuli ($F(1, 15) = 29.7$ and 10.8 , respectively, both $p < 0.005$). The interaction of Frequency Content \times Distractor Letter was not significant ($F < 1$), suggesting that the interference effect did not differ between broadband and CB stimuli. The global-to-local interference was larger than the reverse, resulting in a significant interaction of Level of Attention \times Distractor Letter for both broadband and CB stimuli ($F(1, 15) = 6.42$ and 4.65 , respectively, both $p < 0.05$). Post hoc comparisons confirmed that the global-to-local interference was significant for both sets of stimuli ($F(1, 15) = 43.3$ and 10.2 , respectively, both $p < 0.006$) whereas the local-to-global interference was not significant (broadband: $F(1, 15) = 1.60$, $p > 0.2$; CB: $F < 1$). The interaction of Frequency Content \times Distractor Letter \times Level of Attention did not reach significance ($F < 1$), suggesting that the advantage of global-to-local interference was not different between broadband and CB stimuli. However, the advantage of global-to-local interference was more salient when stimuli were presented in the LVF than in the RVF, reflected by a triple interaction of Level of Attention \times Distractor Letter \times Hemifield ($F(1, 15) = 6.27$, $p < 0.02$).

The RT results are in line with the studies using other methods to reduce SF activity.¹ Lovegrove and Pepper

(1994) showed that adaptation to square wave grating with a SF of 2.8 cpd increased global RTs whereas had little effect on the interference effect. In addition, when responses to blue (a color favors the perception of low SF information, Breitmeyer and Williams, 1990) stimuli showed larger global RT advantage relative to green and red (colors favor the perception of high SF information) stimuli, the interference effect did not vary as a function of stimulus colors. The fact that global RT advantage and global-to-local interference are dissociated by SF manipulations indicates that the interference effect does not require the temporal advantage provided by fast low SF channels.

3.1.2. Hits and false alarms

Hits and false alarm rates are shown in Table 2. Subjects were more accurate in responding to broadband than CB targets (94.9 vs. 89.2%, $F(1, 15) = 10.7$, $p < 0.005$). Accuracy tended to be higher in the global than local conditions (91.3 vs. 89.2%, $F(1, 15) = 3.97$, $p < 0.06$). There was also an interaction between Level of Attention \times Hemifield ($F(1, 15) = 7.38$, $p < 0.02$) due to the fact that subjects detected more local targets in the RVF than in the LVF (91.3 vs. 87.1%) whereas no hemifield difference was seen in the detection of global targets. There was a significant 3-way interaction of Frequency Content \times Level of Attention \times Hemifield ($F(1, 15) = 9.34$, $p < 0.008$), suggesting that the hemifield asymmetry associated with local target detection was larger for CB than for broadband stimuli.

Subjects made fewer false alarms in responding to broadband than to CB stimuli (0.44 vs. 1.50%, $F(1, 15) = 10.1$, $p < 0.006$). The false alarm rates were higher to the RVF relative to the LVF stimuli in the local condition (1.36 vs. 0.75%), whereas a reverse pattern was observed in the global condition (0.72 vs. 1.05%), resulting in a significant interaction of Level of Attention \times Hemifield ($F(1, 15) = 9.04$, $p < 0.009$). The difference in hemifield asymmetry between global and local conditions

Table 2
Accuracy, false alarm rates, and sensitivity (d') in each condition for broadband and CB stimuli (mean \pm SD)

	Global		Local	
	LVF	RVF	LVF	RVF
Accuracy (%)				
Broadband	95.1 \pm 3.98	95.6 \pm 3.92	93.7 \pm 6.14	95.2 \pm 3.55
CB	86.9 \pm 15.9	87.3 \pm 10.6	80.4 \pm 20.1	87.5 \pm 10.8
False alarm (%)				
Broadband	0.35 \pm 0.37	0.39 \pm 0.28	0.43 \pm 0.27	0.61 \pm 0.65
CB	1.76 \pm 2.28	1.07 \pm 1.84	1.07 \pm 1.05	2.11 \pm 2.25
d'				
Broadband	5.10 \pm 1.84	4.52 \pm 0.48	4.33 \pm 0.58	4.71 \pm 1.45
CB	3.67 \pm 1.04	3.75 \pm 0.73	3.50 \pm 1.00	3.53 \pm 0.78

¹ Hughes et al. (1990) found that removing low SFs by contrast balancing reduced global-to-local interference while increased local-to-global interference. However, Hughes et al.'s stimuli were different from those used in our work. For example, in Hughes et al.'s Experiment 1, the global shapes of the hierarchical stimuli were clusters consisting of line segments that were in turn made up of small dots. In Hughes et al.'s Experiment 2, the global shapes of the hierarchical stimuli were squares and diamonds, which were composed of small squares or diamonds that were also made up of small dots. Therefore, there were 3 levels in their hierarchical stimuli. In most of the studies of global/local processing and in our current experiment, however, there are only two levels in the hierarchical stimuli (i.e. there are no clear spatially separated elements in the local shape). In addition, relative to standard solid figures used in most other studies, 'contrast-balanced dots' introduce a lot of new orientation components (particularly in high SF band, see Fig. 3 in Hughes et al.'s paper). Thus, any effect obtained in Hughes et al. may result from the additional level of structure in the compound stimuli or the added orientation components induced by contrast-balanced dots rather than the absence of low SFs.

was less salient for broadband than CB stimuli, indicated by a triple interaction of Frequency Content \times Level of Attention \times Hemifield ($F(1, 15) = 8.05, p < 0.01$).

To examine whether the hemifield asymmetry observed in RT advantage and hits originated from a shift of the decision criteria or differences in the sensitivity of the observer (d'), a signal detection analysis was conducted to calculate d' (Table 1) and subjected to ANOVAs with factors being Frequency Content, Level of Attention, and Hemifield. The ANOVAs revealed a significant effect of Frequency Content ($F(1, 15) = 27.18, p < 0.001$), indicating that the sensitivity was higher to broadband than to CB stimuli. However, the effects of Level of Attention and Hemifield were no longer significant, nor were interactions involving any of these factors ($p > 0.05$), suggesting that d' did not differ between global and local conditions for both broadband and CB stimuli. Therefore, although responses to CB stimuli showed reduced accuracy and increased false alarm rates relative to broadband stimuli, contrast balancing did not differentially affect the sensitivity to global and local targets. In addition, d' measures showed virtually no visual field asymmetry for either global or local conditions, suggesting that the RT asymmetry may reflect, to some unknown degree, the criterion shift.

3.2. Electrophysiological activity

3.2.1. Effects of contrast balancing

ERPs to broadband and CB nontarget stimuli were characterized with a positive wave (P1) followed by a negative component (N1) over lateral occipital sites, as illustrated in Fig. 4. Because ERPs to CB stimuli were significantly delayed relative to broadband stimuli, peak latencies and amplitudes were compared to examine the effects of contrast balancing. As can be seen in Fig. 4, the P1 peaked at about 130 ms at electrodes contralateral to stimulated hemifield for broadband stimuli and at a longer latency (about 150 ms) for CB stimuli. The P1 peak latency

delay arising from contrast balancing was highly significant ($F(1, 15) = 18.0, p < 0.001$). P1 peak amplitudes were also larger to broadband than CB stimuli ($F(1, 15) = 29.3, p < 0.001$), and the P1 in both conditions peaked earlier at electrodes contralateral to the stimulated hemifield ($F(1, 15) = 36.9$ and $52.5, p < 0.001$). Since the visual P1 recorded at occipital areas has generators in extrastriate cortex (Clark et al., 1995; Mangun et al., 1993), the P1 latency delay observed here indicates that the extrastriate cortex responses related to CB stimuli take place later than those related to broadband stimuli. Because CB stimuli contain only high SFs whereas broadband stimuli contain the full range of SFs, these ERP results reflect the well-known differences in integration time and response speed between low and high SF channels (Breitmeyer, 1975; Breitmeyer and Ganz, 1977).

Similarly, the N1 was of shorter peak latency and of smaller peak amplitude for broadband than for CB stimuli ($F(1, 15) = 202.9$ and 12.9 , both $p < 0.003$). In both conditions the N1 showed larger amplitudes ($F(1, 15) = 43.4$ and $77.7, p < 0.001$) and shorter peak latencies ($F(1, 15) = 75.5$ and $35.3, p < 0.001$) at contralateral compared to ipsilateral electrodes. There was a significant positive wave (P2) following the N1 to broadband stimuli, which was also enlarged relative to the P2 to CB stimuli ($F(1, 15) = 18.2, p < 0.001$). The effects of contrast balancing on the P1, N1, and P2 did not differ between global and local conditions ($p > 0.3$ for all) and between the LVF and the RVF stimuli ($p > 0.2$ for all).

Modulations of the P1 and N1 amplitudes by contrast balancing were similar to the results of previous studies using gratings or checkerboard patterns (Bodis-Wollner et al., 1992; Kenemans et al., 2000; Proverbio et al., 1996). However, our data showed that SF-related modulations of these earlier ERP components were not affected by task requirement, suggesting that modulations of the early ERP components by contrast balancing are determined by the intrinsic properties of the SF channels and are largely independent of top-down attention to global or local levels of compound stimuli. Although the task to identify global or local targets has been shown to improve detectability of low and high SF probes, respectively (Shulman and Wilson, 1987), this facilitation may not occur at the level of early representation in the visual cortex, but at a later stage of target perception and evaluation.

This proposal is consistent with the results that modulations of target-related late ERP waves by contrast balancing depended on whether attention was directed to the global structure or individual local elements. As can be seen in Fig. 5, ERPs to targets were characterized with long-latency negative components between 300 and 400 ms at both posterior and anterior sites (denoted as posterior and anterior N2). The posterior N2 was of larger amplitudes at contralateral than ipsilateral electrodes ($F(1, 15) = 15.0$ and $12.0, p < 0.005$ for broadband and CB stimuli, respectively). The posterior N2 showed larger amplitude for

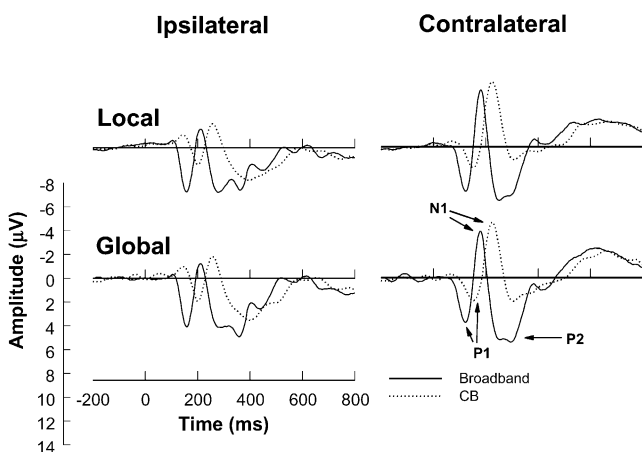


Fig. 4. Effects of contrast balancing on ERPs to nontarget stimuli. For the sake of clarity, only collapsed data at PO7 and PO8 were displayed.

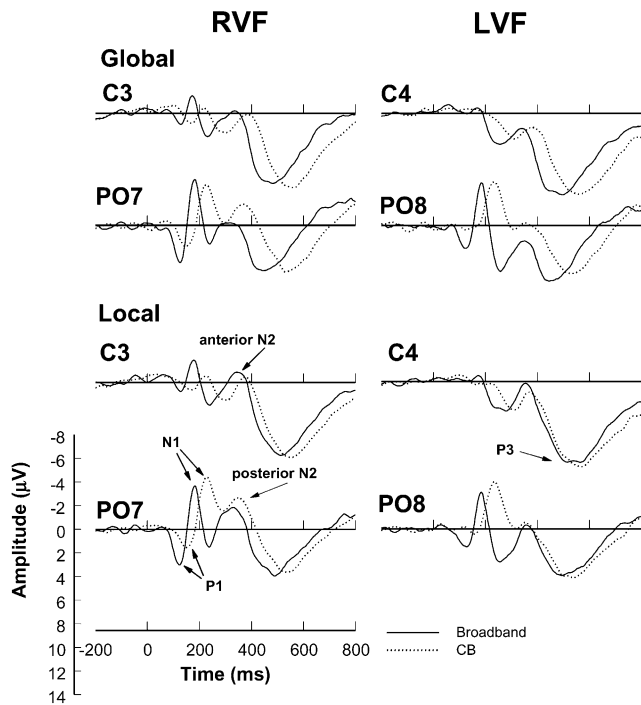


Fig. 5. Effects of contrast balancing on ERPs to target stimuli at central and occipital electrodes contralateral to the stimulated hemifields.

the RVF than the LVF stimuli ($F(1, 15) = 9.10$ and 8.12 , $p < 0.01$ for broadband and CB stimuli, respectively). Contrast balancing enhanced the posterior N2, generating a significant effect of Frequency Content ($F(1, 15) = 7.30$, $p < 0.02$). The posterior N2 peaked earlier to broadband than CB stimuli when presented in the RVF whereas the N2 latencies were not different between the LVF broadband and CB stimuli (see Table 3), resulting in a significant interaction of Frequency Content \times Hemifield ($F(1, 15) = 12.9$, $p < 0.003$). Moreover, the posterior N2 latency delay resulting from contrast balancing was larger for global than local targets ($F(1, 15) = 9.66$, $p < 0.007$).

The ANOVAs conducted over the central and parietal electrodes indicate that the anterior N2 peaked earlier

Table 3

Peak latencies (mean \pm SD, ms) of the posterior N2 (averaged across PO7 and PO8) and the P3 (averaged across P3 and P4) elicited by broadband and CB stimuli

	Global		Local	
	LVF	RVF	LVF	RVF
Posterior N2				
Broadband	325 \pm 29.2	323 \pm 24.7	339 \pm 30.7	327 \pm 25.1
CB	335 \pm 35.9	351 \pm 36.9	331 \pm 34.8	333 \pm 29.2
P3				
Broadband	461 \pm 40.9	471 \pm 38.2	515 \pm 48.2	505 \pm 44.8
CB	539 \pm 39.7	540 \pm 40.9	541 \pm 48.8	542 \pm 46.7

($F(1, 15) = 12.6$, $p < 0.003$) to broadband relative to CB targets. The P3 showed maximum amplitudes over the parietal areas for both broadband and CB targets. The P3 amplitudes did not differ between the two sets of stimuli ($F(1, 15) = 1.3$, $p > 0.2$). However, the P3 latencies were longer to CB than broadband targets ($F(1, 15) = 126.5$, $p < 0.001$, see Table 3). The P3 latency delay was larger for global than local targets, producing a significant interaction of Frequency Content \times Level of Attention ($F(1, 15) = 13.3$, $p < 0.003$). Shorter N2 and P3 latencies and RTs in the local condition to broadband than to CB stimuli probably reflect the processing of local shapes based on medium-high SFs in broadband stimuli. Similar effects in the global condition may reflect both shorter latencies and shorter integration times of low SF channels and earlier global target recognition based on low SF information (see more discussion below).

3.2.2. Effect of global/local attention

To examine the effects of global/local attention and its interaction with contrast balancing manipulation, we compared ERPs in conditions when subjects responded to global and local targets of broadband and CB stimuli, respectively. For broadband nontarget stimuli, differential global/local processing was first evident between 160 and 240 ms over the posterior areas (Fig. 6). This was characterized by enhanced N1 in the local relative to global conditions ($F(1, 15) = 8.04$ to 26.9 , $p < 0.01$). The modulation of the N1 amplitude by global/local attention was more

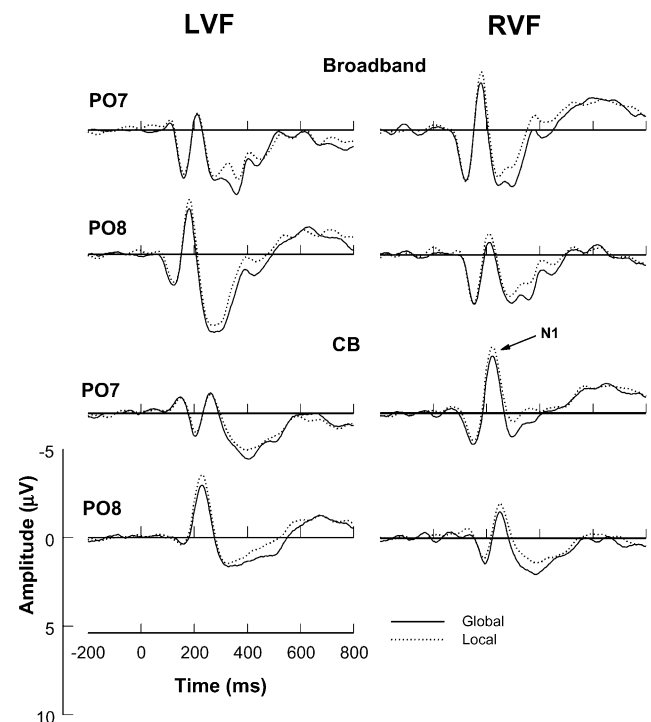


Fig. 6. ERPs to global and local nontarget stimuli at lateral occipital electrodes.

pronounced at contralateral than ipsilateral electrodes as indicated by a significant interaction of Level of Attention \times Hemifield \times Hemisphere ($F(1, 15) = 5.36$ to 19.6 , $p < 0.03$). The second sign of differential global/local processing was a negative shift in local relative to global conditions between 240 and 400 ms at posterior electrodes ($F(1, 15) = 11.1$ to 55.4 , $p < 0.005$).

For CB nontarget stimuli, local processing began to differ from global processing at 180 ms and continued for 120 ms (Fig. 6). This was reflected in larger amplitudes of the posterior N1 in local relative global attention conditions ($F(1, 15) = 6.64$ to 21.7 , $p < 0.02$). This effect was more salient over the hemisphere contralateral to stimulation ($F(1, 15) = 9.52$ to 59.3 , $p < 0.007$). In a later time window (300–500 ms), the ERPs also showed a negative shift in the local relative to global conditions at posterior electrodes ($F(1, 15) = 4.72$ to 8.53 , $p < 0.04$).

The ANOVA combining the data of both broadband and CB stimuli showed a reliable interaction of Frequency Content \times Level of Attention between 300 and 340 ms ($F(1, 15) = 4.91$, $p < 0.04$), reflecting the fact that the negative shift in the local relative to global conditions in this time window was more salient for broadband than CB stimuli (Table 3).

For broadband targets, the difference between global and local processing first emerged between 180 and 200 ms over the posterior sites (Fig. 7). However, unlike ERPs to nontarget stimuli, the N1 was of larger amplitude to the global than local targets ($F(1, 15) = 7.23$, $p < 0.02$), and this effect was stronger at ipsilateral than contralateral electrodes ($F(1, 15) = 9.17$, $p < 0.008$). The second sign of differential global/local target processing started at 280 ms and lasted for 180 ms. Relative to global targets, local targets elicited a larger posterior N2 ($F(1, 15) = 6.89$ to 36.2 , $p < 0.02$). Over the frontal–central sites, the anterior N2 was also of larger amplitudes to local than global targets between 340 and 420 ms ($F(1, 15) = 13.5$, to 13.6 , $p < 0.003$), as shown in Fig. 8. Both the anterior N2 and P3 peaked earlier to global relative to local targets ($F(1, 15) = 7.48$ and 18.3 , respectively, $p < 0.02$ and 0.001 , respectively).

For CB targets, negative enhancements were also seen in local conditions: the differential global/local processing started at 220 ms and continued for 120 ms over the posterior sites ($F(1, 15) = 4.91$ to 9.82 , $p < 0.04$), as illustrated in Fig. 7. This was reflected in enhanced posterior N1 and N2 in the local relative to global conditions.

The ANOVA combining the data of both broadband and CB stimuli showed a significant interaction of Frequency Content \times Level of Attention between 340 and 420 ms at posterior electrodes ($F(1, 15) = 8.19$ to 22.8 , $p < 0.01$), indicating that the posterior N2 enhancement to local relative to global targets was more salient for broadband than CB stimuli.

Modulations of the posterior N2 by global/local attention are consistent with the previous findings (Evans et al., 2000;

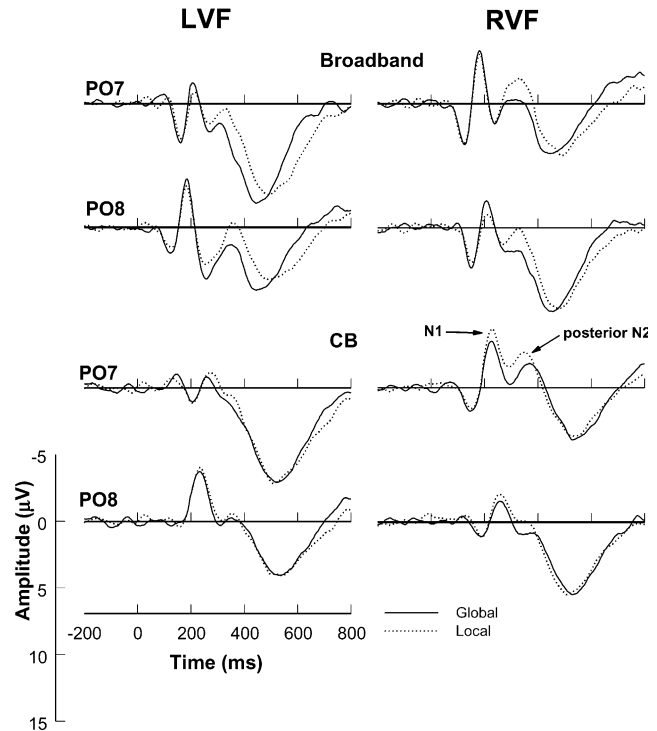


Fig. 7. ERPs to global and local targets at lateral occipital electrodes.

Han et al., 1997, 1999a, 2000a; Heinze et al., 1998). Moreover we found that contrast balancing weakened the negative shift to local relative to global nontarget stimuli and the enlarged posterior N2 to local targets but could not

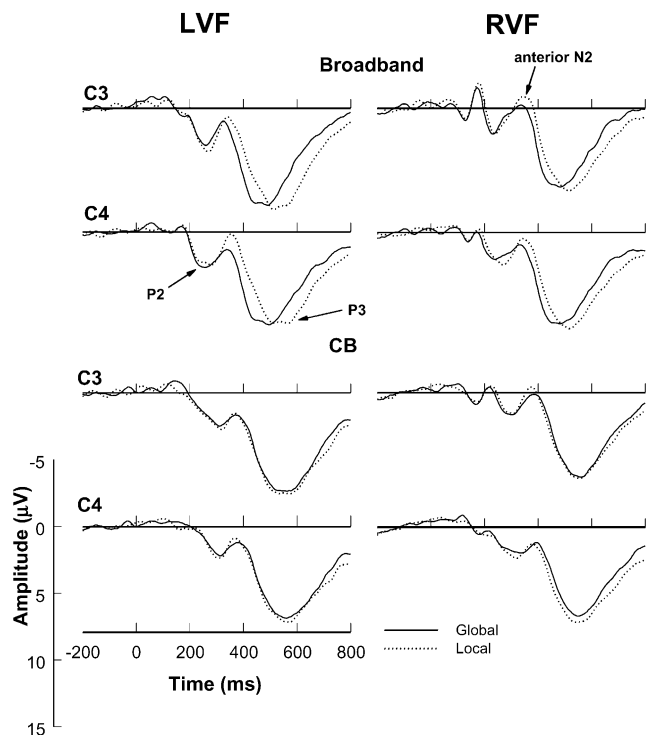


Fig. 8. ERPs to global and local targets at central electrodes.

completely eliminate the effects, suggesting that classification of global/local information based on low SF information contributes only partially to the modulation of the posterior N2. Modulations of the anterior N2 and P3 elicited by targets are also similar to previous reports (Han et al., 1997, 1999a; Proverbio et al., 1998). However, these effects were completely eliminated by contrast balancing, paralleling the RT results. Given these facts and the notion that the anterior N2 component reflects a stage of processing related to stimulus identification (Mulder, 1986; Renault et al., 1982; Ritter et al., 1983) and the P3 latency is associated with processes of stimulus evaluation and categorization (McCarthy and Donchin, 1981; Mecklinger et al., 1993; Mecklinger and Ullsperger, 1993), it may be conjectured that the effect of contrast balancing observed in behavioral data reflects partially the delay of global processing at the stage of stimulus identification and evaluation.

3.2.3. Target specific difference waves

To examine the ERP effects specifically related to target processing, the mean amplitudes of ERPs to target and nontarget stimuli were subjected to ANOVAs with Stimulus Type (target vs. nontarget stimuli), Hemifield, and Hemisphere as independent variables for broadband and CB stimuli, respectively. Target specific difference waves were obtained by subtracting ERPs to nontarget stimuli from those to targets. To illustrate the difference between global and local targets and between broadband and CB stimuli, Fig. 9 shows the difference waves at lateral occipital electrodes contralateral to stimulated hemifields in two ways. The upper row illustrates the difference between global and local target difference waves for broadband and

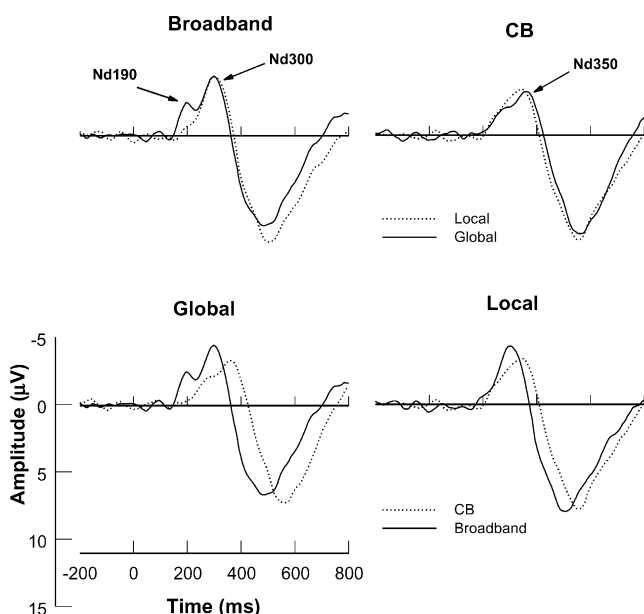


Fig. 9. Target related difference waves at lateral occipital electrodes. Data at PO7 and PO8 were collapsed.

CB stimuli, respectively. The lower row illustrates the difference between broadband and CB stimuli in the global and local conditions, respectively. Broadband global target processing was indexed by two successive negative waves that began at 160 ms and lasted for 180 ms (Nd190 and Nd300, $F(1, 15) = 6.52$ to 30.2 , $p < 0.02$), which were larger at electrodes contralateral to stimulated hemifields ($F(1, 15) = 20.6$ to 73.1 , $p < 0.001$). Broadband local target processing was reflected in only one negative wave over the lateral occipital sites that began at 240 ms and lasted for 140 ms (Nd300, $F(1, 15) = 6.96$ to 26.9 , $p < 0.02$), which was also of larger amplitude at electrodes contralateral to stimulated hemifields ($F(1, 15) = 13.6$, $p < 0.002$). Voltage topographies showed that target-related negativities had distributions over contralateral occipito-temporal areas in both global and local conditions (Fig. 10). Because the target and nontarget stimuli are physically different, it is possible that some of the difference waves between targets and nontargets might reflect the physical difference. However, the physical features of global targets matched well with that of local targets.² Thus the difference between global and local target difference waves should mainly reflect the effect of global/local attentional modulation.

Difference waves related to CB global target processing contained a wide posterior negativity that began at 240 ms and continued for 180 ms (Nd350, $F(1, 15) = 5.28$ to 13.1 , $p < 0.04$), and had larger amplitudes at electrodes contralateral to stimulated hemifields ($F(1, 15) = 11.3$ to 74.9 , $p < 0.001$). CB local target processing was also reflected by an enhanced posterior negativity that began at 240 ms and continued for 180 ms (Nd 350, $F(1, 15) = 8.16$ to 26.5 , $p < 0.02$) with maximum amplitudes over the contralateral hemisphere ($F(1, 15) = 15.7$, $p < 0.002$). Similar to broadband stimuli, both CB global and local target processing related negativities had a distribution over contralateral occipito-temporal areas (see Fig. 10). The ANOVAs were performed to compare the distribution of the early and late phases of target specific difference waves and did not show significant differences between broadband and CB stimuli.

Over the frontal areas, broadband target difference waves included a positivity that began at 220 ms post-stimulus (Pd280, $F(1, 15) = 7.83$, $p < 0.01$), as shown in Fig. 11. The Pd280 was of larger amplitude in the local than global conditions between 260 and 300 ms ($F(1, 15) = 13.2$ to 13.3 , $p < 0.003$), consistent with our previous studies (Han et al., 1999a, 2000a). For CB stimuli, target difference waves over the frontal sites also included a positivity that began at 240 ms (Pd320, $F(1, 15) = 12.2$ to 31.7 , $p < 0.003$). However, the Pd320 amplitude did not differ

² We calculated the total area occupied by the bars composing compound letters. The difference between global and local targets was very small (3.8%). This tiny difference would produce little effect on the difference between global and local target difference waves, particularly on those in a late time window (i.e. Nd190 and Nd300).

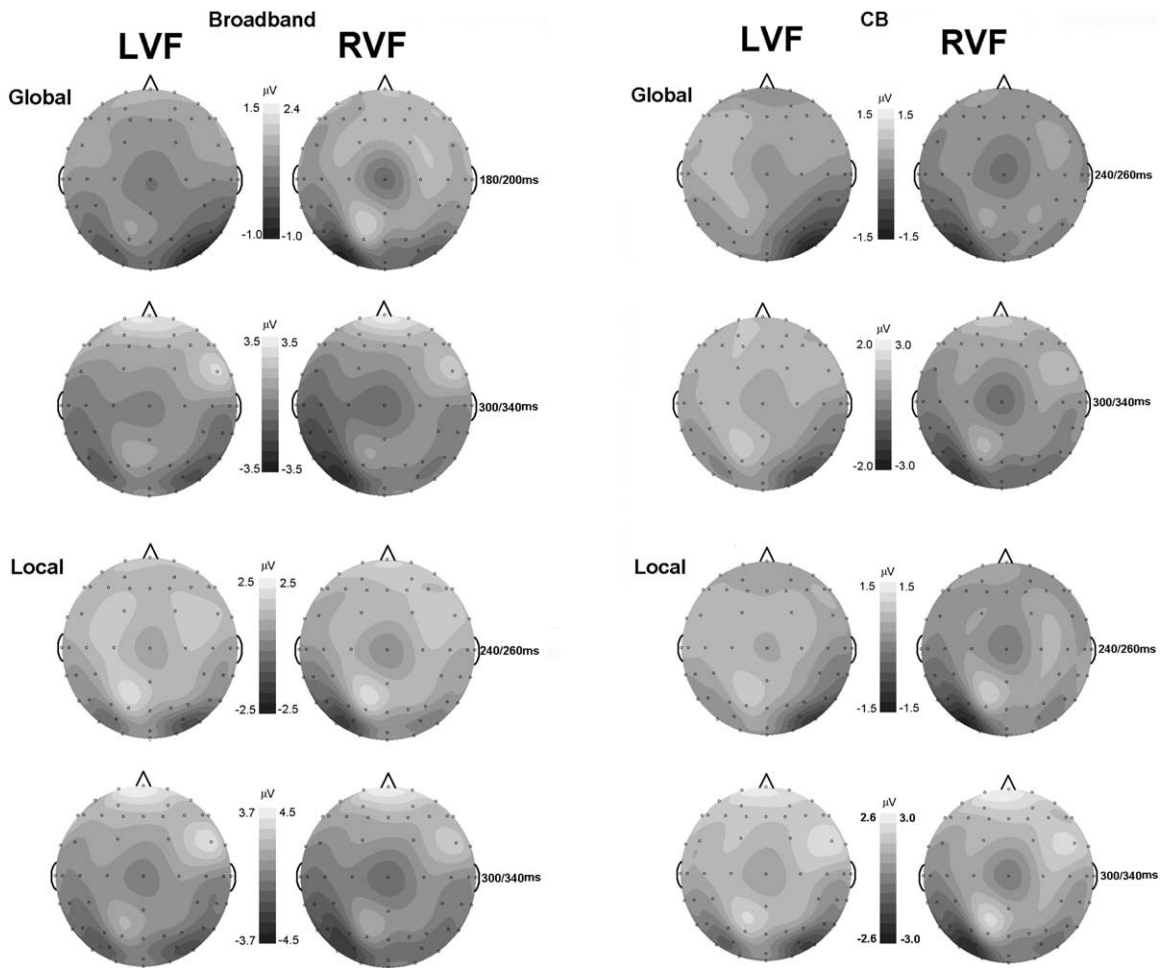


Fig. 10. Voltage topographies of target-related difference waves related to (a) broadband and (b) CB stimuli. The time windows were chosen to show the effects over the posterior areas. The scaling of the voltage differences changes for each time window.

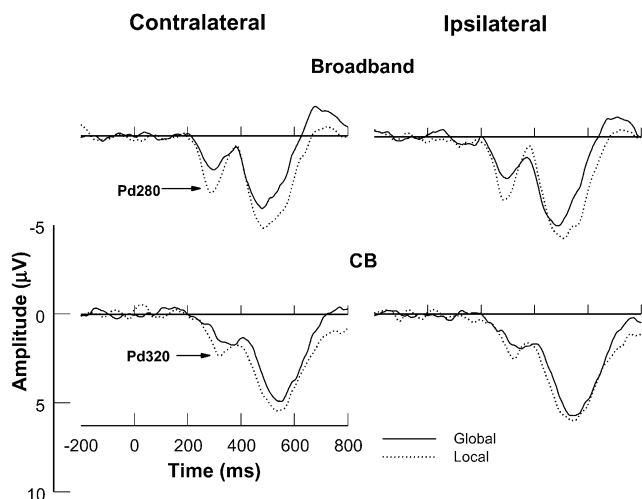


Fig. 11. Target related difference waves at frontal electrodes. Data at F3 and F4 were collapsed.

between global and local conditions ($F(1, 15) = 3.3$, $p > 0.08$). As previous research has suggested that the frontal lobes are involved in inhibition of distractors (Knight et al., 1980, 1981, 1999), it is possible that the stronger frontal activity in the local relative to global tasks reflects neural mechanisms involved in inhibiting competitive global processing when low SFs are available in the stimuli. Contrast balancing makes global features less salient and less competitive during the local task, and thus reduces the need for stronger frontal activity in the local than in the global condition.

3.2.4. Interference effects

The interference effect was examined by comparing ERPs elicited by target stimuli when shapes at unattended levels were similar or dissimilar to those at attended levels (Fig. 12 only illustrates the interference effect in the local condition since no significant interference was observed in the global condition, see below). For broadband stimuli, the first sign of interference was observed between 180 and 200 ms after stimulus onset, as reflected by significant effect

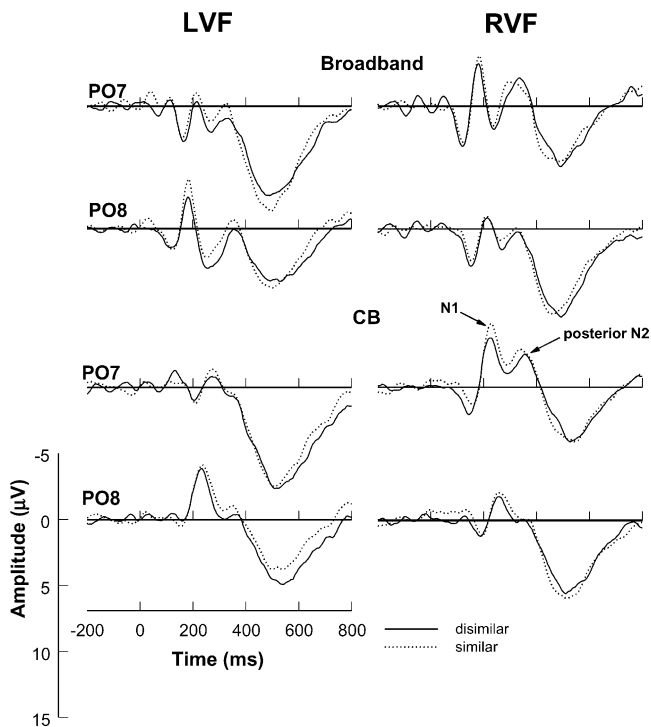


Fig. 12. ERPs to local targets with similar or dissimilar global shapes at lateral occipital electrodes.

of Distractor Letter ($F(1, 15) = 6.70, p < 0.02$). The N1 was enlarged when distractors were similar rather than dissimilar to targets in shapes. As the interaction of Level of Attention \times Distractor Letter was also significant ($F(1, 15) = 4.87, p < 0.04$), post hoc comparisons were conducted for global and local conditions separately. This revealed a significant interference effect on local processing ($F(1, 15) = 9.16, p < 0.01$) but not on global processing ($F < 1$). There was also a reliable interaction of Level of Attention \times Distractor Letter between 240 and 300 ms over lateral occipital sites ($F(1, 15) = 4.89$ to $9.02, p < 0.04$). Post hoc comparisons showed that there was a negative shift in the rising phase of the posterior N2 to local targets when global shapes were similar relative to dissimilar to local shapes ($F(1, 15) = 12.7$ to $18.4, p < 0.003$), whereas no interference effect was found on global processing ($F < 1$).

Similarly, for CB stimuli, there was a reliable interaction between Level of Attention and Distractor Letter at 240–340 ms over lateral occipital sites ($F(1, 15) = 4.87$ to $16.4, p < 0.04$). Post hoc comparisons also showed enhancement of the N1 and a negative shift in the rising phase of the posterior N2 in the local condition when global shapes were similar relative to dissimilar to local shapes ($F(1, 15) = 5.48$ to $16.2, p < 0.03$), whereas no interference effect was found in the global condition ($p > 0.2$).

The global-to-local interference was localized in voltage topographies of the difference waves made by subtracting

ERPs to local targets with dissimilar global shapes from ERPs to local targets with similar global shapes. As can be seen in Fig. 13, the interference effect showed a distribution over the occipito-temporal areas for both broadband and CB stimuli. This effect appeared to be larger contralateral to stimulated hemifield, but was significant between 300 and 340 only for CB stimuli ($F(1, 15) = 6.59, p < 0.02$). The ANOVAs did not show significant difference in the distribution of global-to-local interference between broadband and CB stimuli.

4. Discussion

4.1. The role of low SFs in the global precedence effect

Previous behavioral studies manipulating SF contents of compound stimuli showed that global RT advantage was eliminated by high-pass filtering (Badcock et al., 1990) or contrast balancing (Lamb and Yund, 1993, 1996b). Similar behavioral results were observed in the current study. In addition, we provide ERP evidence that broadband global target processing was characterized by a short-latency negativity (Nd190) followed by a long-latency negativity (Nd300) whereas broadband local target processing was indexed with only the long-latency negativity (Nd300). These are consistent with the results in our previous work (Han et al., 2000a) that employed a divided attention procedure and central presentation of compound shapes. More interestingly, we found that the Nd190 to broadband global targets was eliminated by removing low SFs, as

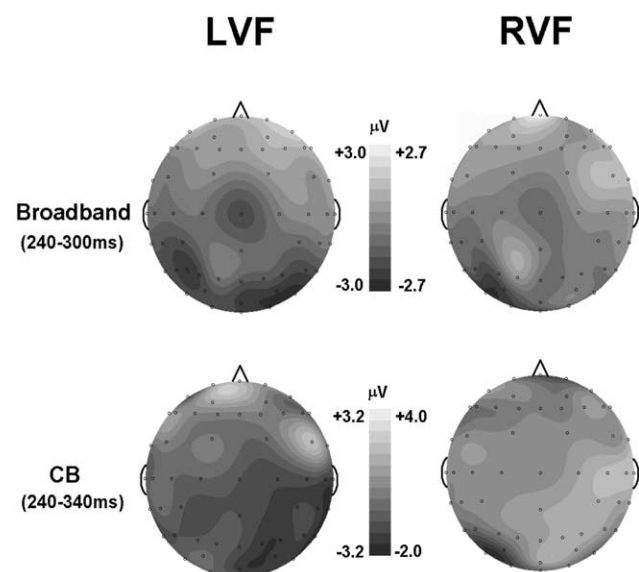


Fig. 13. Voltage topographies showing the locations of the global-to-local interference effect. Average voltage differences were obtained by subtracting ERPs to local targets with dissimilar global shapes from ERPs to local targets with similar global shapes.

indexed by the difference wave to CB global targets.³ The ERP results provide electrophysiological evidence that global target processing started earlier than local target processing when low SFs were available in compound stimuli (indexed by Nd190). Local target processing of broadband stimuli, however, took place at a later time window (indexed by Nd300) that corresponded to the late stage of global target processing. When low SFs were removed from the stimuli, the early global target processing was attenuated. The Nd300 was delayed by contrast balancing (i.e. the Nd350 for both global and local target processing of CB stimuli), but this effect was similar for both global and local targets. Consequently the global and local target processing was approximately equally fast.

These results clarify two distinct neural mechanisms underlying global target processing. First, there is an early low-SF-based processing of global targets. Contrast balancing eliminates this process rather than simply slowing it. Second, a late global target processing occurs regardless of the presence of low SFs, but was delayed by contrast balancing. The early low-SF-based processing coexisted with global RT advantage whereas the peak latencies of the late global target processing did not differ from those of local target processing under both circumstances where global RT advantage was present or not. Therefore, our results support a model in which the role of low SFs in global precedence is, at least partially, to support an early process of global target perception. High-pass filtering or contrast balancing weakens the global precedence effect by eliminating rather than delaying this early process.

This model helps to account for the modulations of early ERP components by global/local attention. For example, it may be suggested that the N1 enhancement seen for broadband global targets relative to local targets observed in the current experiment reflects an early discrimination of global targets. This is in agreement with the proposal that the enlarged N1 reflects a general mechanism involved in discrimination processes based on different visual feature dimensions (Ritter et al., 1983, 1988; Ritter et al., 1982; Vogel and Luck, 2000). In addition, as this early

discrimination of global targets is based on low SFs in stimulus displays, this model can thus interpret the difference in N1 modulations by global/local attention between broadband and CB target stimuli.

For nontarget stimuli, however, the N1 modulation by global/local attention may reflect mechanisms independent of target discrimination. For instance, during a local task, subjects had to select a local figure from compound stimuli for further shape analysis because each of the local items was equally task relevant (Han et al., 1999b, 2001; Han and Humphreys, 2002). Furthermore, it is important that subjects choose one complete local item because incomplete targets and nontargets may be indistinguishable in the stimulus font (e.g. the top halves of S and E are the same, and the H and A differ only at the very top) and parts of adjacent nontargets may be target-like (e.g. the top of one A and the bottom of the A above it correspond to one H-like shape). Thus, orienting of attention to a specific local item in a global structure would be essential for local processing, whereas no such orienting of attention is necessary for global processing where only one global shape is present at any time. Because researchers have demonstrated that the N1 enhancement reflects orienting of spatial attention to a task-relevant stimulus (Heinze et al., 1990; Luck et al., 1990; Mangun and Hillyard, 1990), it may be conjectured that the orienting of attention to a specific local element contributed to the N1 enhancement in the local relative to global condition for broadband nontarget stimuli. In addition, such orienting process is space-based rather than low-SF-based. This can account for the N1 enhancement in the local relative to the global condition for CB nontarget stimuli. It should be pointed out that the interpretations of the N1 modulations by global/local attention and contrast balancing provided here are in the nature of post hoc speculations, which need further experiments to testify.

4.2. Mechanisms of global-to-local interference effect

For broadband stimuli, the global-to-local interference was characterized by enhanced N1 and the rising phase of the posterior N2 with a lateral occipito-temporal distribution. The modulations of the posterior negativities by global/local shape congruency were similar to previous studies (Proverbio et al., 1998). The locus of the interference effect is consistent with that of patient studies (Lamb et al., 1989), which showed that lesions centered in the posterior superior temporal gyrus eliminated behavioral global-to-local interference observed in normal subjects. Interestingly, similar patterns of ERP modulation by global/local shape congruency was found for CB stimuli, suggesting that neural mechanisms underlying the global-to-local interference is independent of the presence of low SFs in the compound stimuli.

Some researchers suggest that the interference between global and local properties of compound stimuli results from inhibitory interactions between high and low SF channels

³ Target difference waves to CB global targets showed clearly only one negative peak (i.e. Nd350). However, as one reviewer pointed out, the shoulder in the rising phase of the Nd350 might be an early peak though not as clear as the Nd190 in the target difference waves to broadband global targets. To test this hypothesis, principle component analyses of target difference waves to broadband and CB global targets were conducted using Curry 4.5 in the time window including the early Nd190 to broadband global targets and the shoulder in the rising phase of the Nd350 to CB global targets. It turned out that there were two components with eigenvalues larger than one for broadband global targets. In particular, one component peaked at a time point close to 190 ms post-stimulus. There was only one component with eigenvalue larger than one for CB global targets, and this component did not show any peak at the time corresponding to the shoulder in the rising phase of the Nd350. The results of principle component analyses suggest that the shoulder in the rising phase of the Nd350 to CB global targets was not an ERP component as the Nd190 in the target difference wave to broadband global targets, but might be simply a noise.

(Hughes et al., 1990; Kitterle et al., 1993). However, our ERP results lend little support for this hypothesis. Since low SFs were not available in CB stimuli, it is unlikely that the ERP signs of global-to-local interference reflect SF-based sensory-level interaction. Because the largest effect of global-to-local interference was found as early as 200 ms post-stimulus over the lateral occipito-temporal cortex that is involved in object perception and recognition (Kourtzi and Kanwisher, 2000; Logothetis and Sheinberg, 1996), it may suggest that mechanisms at the level of object perception and recognition contribute to the interference between global and local processing.

One of the key differences between global and local processing is that there is only one object (i.e. a global letter) in the field relevant to the global task whereas multiple objects (i.e. local letters) are present for the local task (Han et al., 1999b; Han and Humphreys, 2002). Accordingly, global representation may be directly compared with an internal template for recognition during the global task. For the local task, however, one local element must be selected before matching the representation of local shapes with the internal template. Because of the additional selection process involved in the local task, representation of global shapes may dominate in competition with representations of local shapes during the matching process. During a local task, when global and local shapes are similar or identical, the matching process is enhanced because information from both levels of compound stimuli fits well with the template. In contrast, when global and local shapes are dissimilar or conflicting, the matching process is inhibited. The negative shift of the posterior activities in the condition when the distractor letter was similar to targets (observed here) may reflect the enhanced matching process. Although removing low SF from compound stimuli delayed earlier global representation, it did not eliminate global-to-local interference possibly because the matching process took place after representations of global and local shapes. Therefore, the mechanism underlying the interference effect suggested here is independent of the presence of low SF and the relative speed of global and local responses. However, when stimulus information was transmitted only through high SF channels, the process of matching local representation with internal templates might also be delayed. This may account for our results that the ERP signs of global-to-local interference took place later for CB than broadband stimuli.

4.3. Hemispheric organization of global/local processing

While the results of response speed and target hits suggest hemispheric asymmetry of global/local processing, the d' analysis showed no hemifield asymmetry for either global or local tasks in either broadband or CB stimulus conditions. The lack of asymmetry in the signal detection analysis indicates that the asymmetries in RTs and hits might be due to differences in response criteria. In agreement with the signal detection analysis, ERPs in the global and local

conditions did not show consistent hemispheric asymmetries. The only interaction between SF and hemifield observed here indicates that the posterior N2 peaked earlier to broadband relative to CB stimuli when stimuli were presented in the RVF whereas no difference was found between the LVF broadband and CB stimuli. However, this pattern is opposite to the prediction of Sergent's (1982) hypothesis that the right and left hemispheres dominate low and high SF processing, respectively.

How can the present results be reconciled with previous studies that showed lateralized brain activities during global and local processing? For example, by measuring regional cerebral blood flow (rCBF), Fink et al. (1996) found that attention to the global aspect of compound letters activated the right lingual gyrus whereas locally directed attention activated the left inferior occipital cortex in a selective attention task. Martinez et al. (1997) also observed stronger functional magnetic resonance imaging (fMRI) signals over the right inferior temporal cortex during the global than during the local tasks. Similarly, previous ERP studies showed that the N2 amplitudes were larger to local than to global targets over the left hemisphere (Heinze et al., 1994, 1998), and global and local target difference waves were larger over the right and left hemispheres, respectively (Han et al., 2000a,b). In these studies, the compound stimuli were displayed centrally, whereas the stimuli were displayed unilaterally in the present experiment. It appears that stimulus position may be critical for the emergence of reliable hemispheric asymmetries in global/local processing.⁴ This notion is supported by our recent fMRI study (Han et al., 2002), which showed that, while central broadband stimuli induced stronger activation in the right lateral occipital cortex in the global attention condition and in the left lateral occipital cortex in the local attention condition, this asymmetry was eliminated by presenting the stimuli unilaterally.

Acknowledgements

This work was supported by National Institutes of Mental Health (NIMH-41544), the VA Research Service, National Natural Science Foundation of China (Project 30225026), the Ministry of Science and Technology of China (2002CCA01000), and the Scientific Research Foundation

⁴ The strategy of processing in the two hemispheres may be quite different between the conditions of central and unilateral presentations. For central presentation, the two hemispheres have simultaneous access to stimulus information and compete for the processing of stimuli. It is possible that the competition results in the use of relatively more resources in the right hemisphere to process the global information and relatively more resources in the left hemisphere to process the local information. When compound stimuli are presented unilaterally, however, the contralateral hemisphere does the primary stimulus processing at the appropriate level before the information is transferred to the ipsilateral hemisphere through the corpus callosum. The time difference in access to the original information may eliminate the competition between the two hemispheres.

for the Returned Overseas Chinese Scholars, State Education Ministry, Peking University. We thank Janelle Weaver for help in collecting data, and Lynn Robertson and Kimmo Alho for their comments.

References

- Badcock JC, Whitworth FA, Badcock DR, Lovegrove WJ. Low-frequency filtering and the processing of local–global stimuli. *Perception* 1990; 19:617–29.
- Bodis-Wollner I, Brannan JR, Nicoll J, Frkovic S, Mylin LH. A short latency cortical component of the foveal VEP is revealed by hemifield stimulation. *Electroenceph clin Neurophysiol* 1992;84:201–8.
- Breitmeyer BG. Simple reaction time as a measure of the temporal response properties of transient and sustained channels. *Vision Res* 1975;15: 1411–2.
- Breitmeyer BG, Ganz L. Temporal studies with flashed gratings: inferences about human transient and sustained channels. *Vision Res* 1977;17: 861–5.
- Breitmeyer BG, Williams M. Effects of isoluminant-background color on metacontrast and stroboscopic motion: interactions between sustained (P) and transient (M) channels. *Vision Res* 1990;30:1069–75.
- Christman S, Kitterle FL, Niebauer CL. Hemispheric asymmetries in the identification of band-pass filtered letters. *Psychon Bull Rev* 1997;4: 277–84.
- Clark VP, Fan S, Hillyard SA. Identification of early visual evoked potential generated by retinotopic and topographic analyses. *Hum Brain Mapp* 1995;2:170–87.
- Delis D, Robertson LC, Efron R. Hemispheric specialization of memory for visual hierarchical stimuli. *Neuropsychologia* 1986;24:205–14.
- Evans MA, Shedden JM, Hevenor SJ, Hahn MC. The effect of variability of unattended information on global and local processing: evidence for lateralization at early stages of processing. *Neuropsychologia* 2000;38: 225–39.
- Fink GR, Halligan PW, Marshall JC, Frith CD, Frackowiak RSJ, Dolan RJ. Where in the brain does visual attention select the forest and the trees? *Nature* 1996;382:626–8.
- Grice GR, Canham L, Boroughs JM. Forest before trees? It depends where you look. *Percept Psychophys* 1983;33:121–8.
- Han S, Chen L. Processing of global and local properties—an analysis with event-related brain potentials. *Sci China C Life Sci* 1996;39: 179–88.
- Han S, Humphreys GW. Interactions between perceptual organization based on Gestalt laws and those based on hierarchical processing. *Percept Psychophys* 1999;6:1287–98.
- Han S, Humphreys GW. Segmentation and selection contribute to local processing in hierarchical analysis. *Q J Exp Psychol A* 2002;55: 5–21.
- Han S, Fan S, Chen L, Zhuo Y. On the different processing of wholes and parts: a psychophysiological study. *J Cogn Neurosci* 1997;9: 686–97.
- Han S, Fan S, Chen L, Zhuo Y. Modulation of brain activities by hierarchical processing: a high-density ERP study. *Brain Topogr* 1999a; 11:171–83.
- Han S, Humphreys GW, Chen L. Parallel and competitive processes in hierarchical analysis: perceptual grouping and encoding of closure. *J Exp Psychol Hum Percept Perform* 1999b;25:1411–32.
- Han S, He X, Woods DL. Hierarchical processing and level-repetition effect as indexed by early brain potentials. *Psychophysiology* 2000a;37: 817–30.
- Han S, Liu W, Yund EW, Woods DL. Interactions between spatial attention and global/local feature selection: an ERP study. *NeuroReport* 2000b; 12:2753–8.
- Han S, He X, Yund EW, Woods DL. Attentional selection in the processing of hierarchical patterns: an ERP study. *Biol Psychol* 2001;5:31–48.
- Han S, Weaver J, Murray S, Yund EW, Woods DL. Hemispheric asymmetry in global/local processing: effects of stimulus position and spatial frequency. *Neuroimage* 2002;17:1290–9.
- Heinze HJ, Münte TF. Electrophysiological correlates of hierarchical stimulus processing: dissociation between onset and later stages of global and local target processing. *Neuropsychologia* 1993;31: 841–52.
- Heinze HJ, Luck SJ, Mangun GR, Hillyard SA. Lateralized visual ERPs index focused attention to bilateral stimulus arrays: I. Evidence for early selection. *Electroenceph clin Neurophysiol* 1990;75:511–27.
- Heinze HJ, Johannes S, Münte TF, Mangun GR. The order of global- and local-level information processing: electrophysiological evidence for parallel perception processes. In: Heinze H, Munte T, Mangun GR, editors. *Cognitive electrophysiology*. Boston, MA: Birkhauser; 1994. p. 1–25.
- Heinze HJ, Hinrichs H, Scholz M, Burchert W, Mangun GR. Neural mechanisms of global and local processing. A combined PET and ERP study. *J Cogn Neurosci* 1998;10:485–98.
- Hughes HC, Layton WM, Baird JC, Lester LS. Global precedence in visual pattern recognition. *Percept Psychophys* 1984;35:361–71.
- Hughes HC, Fendrich R, Reuter-Lorenz PA. Global versus local processing in the absence of low spatial frequencies. *J Cogn Neurosci* 1990;2: 272–82.
- Ivry RB, Robertson LC. *Two sides of perception*. Cambridge, MA: MIT Press; 1998.
- Kenemans JL, Baas JM, Mangun GR, Lijffijt M, Verbaten MN. On the processing of spatial frequencies as revealed by evoked-potential source modeling. *Clin Neurophysiol* 2000;111:1113–23.
- Kitterle FL, Selig LM. Visual field effects in the discrimination of sine-wave gratings. *Percept Psychophys* 1991;50:15–18.
- Kitterle FL, Christman S, Conesa J. Hemispheric differences in the interference among components of compound gratings. *Percept Psychophys* 1993;54:785–793.
- Knight RT, Hillyard SA, Woods DL, Neville HJ. The effects of frontal and temporal–parietal lesions on the auditory evoked potential in man. *Electroenceph clin Neurophysiol* 1980;50:112–24.
- Knight RT, Hillyard SA, Woods DL, Neville HJ. The effects of frontal vortices lesions on evoked potentials during auditory selection. *Electroenceph clin Neurophysiol* 1981;52:571–82.
- Knight RT, Staines WR, Swick D, Chao LL. Prefrontal cortex regulates inhibition and excitation in distributed neural networks. *Acta Psychol* 1999;101:159–78.
- Kourtzi Z, Kanwisher N. Representation of perceived object shape by human lateral occipital complex. *Science* 2000;293:1506–9.
- Lagasse L. Effects of good form and spatial frequency on global precedence. *Percept Psychophys* 1993;53:89–105.
- Lamb MR, Robertson LC. Do response time advantage and interference reflect the order of processing of global- and local-level information? *Percept Psychophys* 1989;46:254–8.
- Lamb MR, Yund EW. The role of spatial frequency in the processing of hierarchically organized stimuli. *Percept Psychophys* 1993;47:489–96.
- Lamb MR, Yund EW. Spatial frequency and attention: effect of level-, target-, and location-repetition on the processing of global and local forms. *Percept Psychophys* 1996a;58:363–73.
- Lamb MR, Yund EW. Spatial frequency and interference between global and local level of structure. *Vis Cogn* 1996b;3:193–219.
- Lamb MR, Yund EW. The role of spatial frequency in cued shifts of attention between global and local forms. *Percept Psychophys* 2000;62: 753–61.
- Lamb MR, Robertson LC, Knight RT. Attention and interference in the processing of global and local information: effects of unilateral temporal–parietal junction lesions. *Neuropsychologia* 1989; 27:471–83.
- Lamb MR, Robertson LC, Knight RT. Component mechanisms underlying the processing of hierarchically organized patterns: inferences from

- patients with unilateral cortical lesions. *J Exp Psychol Learn Mem Cogn* 1990;16:471–83.
- Lamb MR, Yund EW, Pond HM. Is attentional selection to different levels of hierarchical structure based on spatial frequency? *J Exp Psychol Gen* 1999;128:88–94.
- Logothetis NK, Sheinberg DL. Visual object recognition. *Annu Rev Neurosci* 1996;19:577–621.
- Lovegrove W, Pepper K. The influence of low-level processing in the global precedence effect. In: Ballesteros S (Ed.), *Cognitive approach to human perception*. Hillsdale, New Jersey; 1994. p. 71–90.
- Luck SJ, Heinze HJ, Mangun GR, Hillyard SA. Visual event-related potentials index focused attention within bilateral stimulus arrays. II. Functional dissociation of P2 and N2 components. *Electroenceph clin Neurophysiol* 1990;75:528–42.
- Mangun GR, Hillyard SA. Allocation of visual attention to spatial locations: tradeoff functions for event-related brain potentials and detection performance. *Percept Psychophys* 1990;47:532–50.
- Mangun GR, Hillyard SA, Luck SJ. Electro-cortical substrates of visual selective attention. In: Meyer DE, Kornblum S, editors. *Attention and performance*, XIV. Cambridge, MA: MIT Press; 1993. p. 219–43.
- Martinez A, Moses P, Frank L, Buxton R, Wong E, Stiles J. Hemispheric asymmetries in global and local processing: evidence from fMRI. *NeuroReport* 1997;8:1685–9.
- McCarthy G, Donchin E. A metric for thought: a comparison of P300 latency and reaction time. *Science* 1981;211:77–80.
- Mecklinger A, Ullsperger P. P3 varies with stimulus categorization rather than probability. *Electroenceph clin Neurophysiol* 1993;86:395–407.
- Mecklinger A, Ullsperger P, Baldeweg T. In search of the internal model: P300 amplitude in a multiple stimulus paradigm. In: Heinze H-J, Münte TF, Mangun GR, editors. *New developments in event-related potentials*. Boston, MA: Birkhauser; 1993. p. 131–5.
- Mulder G. The concept and measure of mental effort. In: Robert G, Hockey J, Gaillard AWK, Coles MGH, editors. *Energetics and human information processing*. Dordrecht, The Netherlands: Martinus Nijhoff Publishers; 1986. p. 175–98.
- Navon D. Forest before trees: the precedence of global features in visual perception. *Cogn Psychol* 1977;9:353–83.
- Pomerantz JR. Global and local precedence: selective attention in form and motion perception. *J Exp Psychol Gen* 1983;112:512–40.
- Proverbio AM, Zani A, Avella C. Differential activation of multiple current sources of foveal VEPs as a function of spatial frequency. *Brain Topogr* 1996;9:59–68.
- Proverbio AM, Minniti A, Zani A. Electrophysiological evidence of a perceptual precedence of global vs. local visual information. *Cogn Brain Res* 1998;6:321–34.
- Renault B, Ragot R, Lesevre N, Remond A. Onset and offset of brain events as indices of mental chronometry. *Science* 1982;215:1413–5.
- Ritter W, Simson R, Vaughan HG, Macht M. Manipulation of event-related potential manifestations of information processing stages. *Science* 1982;218:909–911.
- Ritter W, Simson R, Vaughan HG. Event-related potential correlates of two stages of information processing in physical and semantic discrimination task. *Psychophysiology* 1983;20:168–79.
- Ritter W, Simson R, Vaughan HG. Effects of the amount of stimulus information processed on negative event-related potentials. *Electroenceph clin Neurophysiol* 1988;69:244–58.
- Robertson LC. Attentional persistence for features of hierarchical patterns. *J Exp Psychol Gen* 1996;125:227–49.
- Robertson LC, Lamb MR, Knight RT. Effects of lesions of temporal–parietal junction on perceptual and attentional processing in humans. *J Neurosci* 1988;8:3757–69.
- Robertson LC, Lamb MR, Zaidel E. Callosal transfer and hemisphere laterality in response to hierarchical patterns: evidence from normal and commissurotomy subjects. *Neuropsychology* 1993;7:325–42.
- Sergent J. The cerebral balance of power: confrontation or cooperation? *J Exp Psychol Hum Percept Perform* 1982;8:253–72.
- Shulman GL, Wilson J. Spatial frequency and selective attention to local and global information. *Perception* 1987;16:89–101.
- Shulman GL, Sullivan MA, Gish K, Sakoda WJ. The role of spatial frequency channels in the perception of local and global structure. *Perception* 1986;15:259–79.
- Stöffer TH. Attentional zooming and the global-dominance phenomenon: effects of level-specific cueing and abrupt visual onset. *Psychol Res* 1994;56:83–98.
- Vogel EK, Luck SJ. The visual N1 component as an index of a discrimination process. *Psychophysiology* 2000;37:190–203.
- Ward LM. Determinants of attention to local and global features of visual forms. *J Exp Psychol Hum Percept Perform* 1982;8:562–81.