
Hierarchical processing and level-repetition effect as indexed by early brain potentials

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Abstract

Event-related potentials were recorded to investigate the mechanisms of hierarchical processing and level-repetition effect. Participants identified targets that appeared at global, local, or both levels of hierarchical patterns. Reaction times showed global precedence and level-repetition effects. An occipital P1 wave was enhanced to local relative to global targets. The P1 to local targets was also larger when preceded by global than local targets. Global and both-level target selections were indexed by two posterior negativities peaking at 130 and 190 ms poststimulus, whereas local target selection was indexed by a broad occipitotemporal negativity. A late selection positivity was observed over the left occipitotemporal site for global targets but over the central site for local targets. The findings suggest that sensory-perceptual mechanisms contribute to global precedence and level-repetition effects in hierarchical processing.

Descriptors: ERPs, Hierarchical processing, Level-repetition effect, Global precedence, Grouping

Event-related brain potentials (ERPs) reflect the synchronous activation of neuronal populations engaged in perceptual and cognitive processing and have been widely used to study neural mechanisms of visual attention. For example, Hillyard, Mangun, and colleagues (Hillyard, Mangun, Woldorff, & Luck, 1995; Hopfinger & Mangun, 1998; Mangun & Hillyard, 1988, 1990, 1991) have shown that spatial selective attention reliably enhances the amplitudes of P1 beginning at latencies of 50 ms.

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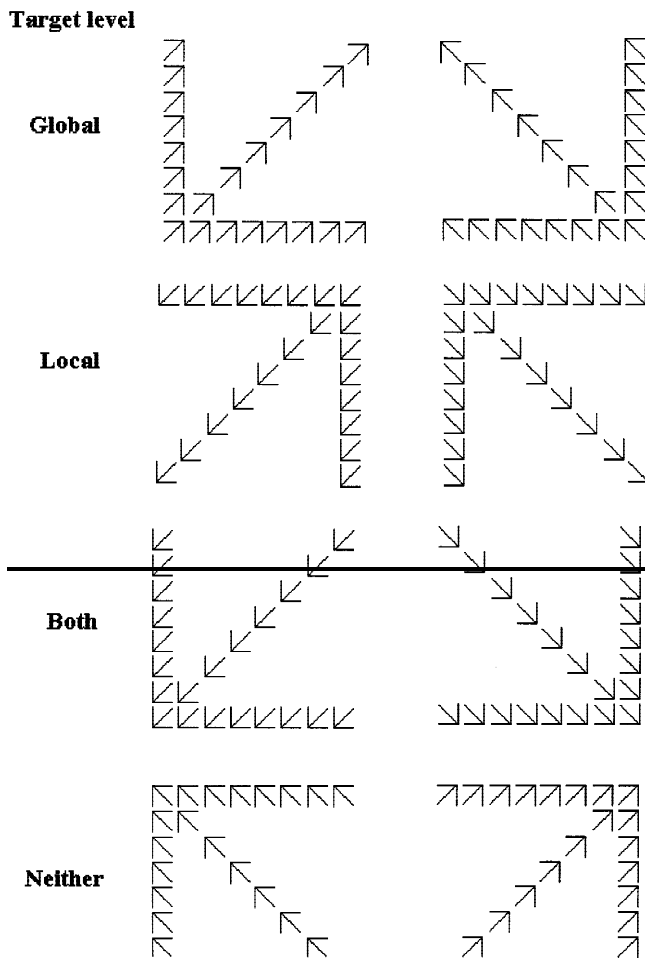


Figure 1. Hierarchical patterns used in the present study.

Heinze and Münte (1993) examined ERP correlates of global and local processing of hierarchical stimuli. They had subjects respond to target letters that could appear at either the global or local levels of compound stimuli with equal probability (a divided attention procedure). They found that the onset and amplitude of a posterior negative component (N250) were related to processing dominance of global or local levels shown in behavioral data, being earlier and larger to local than global targets when local responses were faster than global responses. Heinze, Münte, and Mangun (1994) further observed that the N250 amplitudes were higher to local than to global targets over the left hemisphere, whereas the N250 amplitudes in the two conditions were about the same over the right hemisphere. Therefore, they suggested that the N250 indexed the early global/local target perception in the right and left hemispheres.

Han, Fan, Chen, and Zhuo (1997), using a selective attention procedure, recorded ERPs to the identification of global or local shapes of hierarchical stimuli (such as those in Figure 1) presented in the center of the visual field. Han et al. found an enlargement of an occipital N2 component to the identification of local relative to global stimuli. In addition, the amplitude of an early occipital P1 component (80–120 ms) was modulated by hierarchical processing, being larger when attention was directed to local than global features. This P1 effect was confirmed in studies using compound letters presented in the center or periphery of the visual field (Han

& Chen, 1996; Han, Fan, Chen, & Zhuo, 1999). Recent work by Han, Liu, Yund, and Woods (2000) showed that the occipital P1 could be modulated simultaneously by spatial attention and attention to global or local levels of hierarchical patterns. While the P1s evoked by hierarchical stimuli were enlarged at spatially attended relative to unattended locations, local feature selection also enhanced the P1 relative to global feature selection. Taken together, these findings suggest that modulations of brain potentials by hierarchical processing may occur at the early sensory-perceptual levels where spatial selective attention also operates.

While Han et al.'s previous work using the selective attention procedure found evidence for modulation of the P1 component by hierarchical processing, other studies using divided attention procedures have not observed a P1 effect (Heinze & Münte, 1993; Heinze, Münte, & Mangun, 1994; Heinze, Hinrichs, Scholz, Burchert, & Mangun, 1998; Johannes, Wieringa, Matzke, & Münte, 1996; Proverbio, Minniti, & Zani, 1998). The first objective of the current study was to determine if the P1 effect observed in Han et al.'s studies could be obtained in divided attention conditions. Compound shapes (i.e., global arrows made up of local arrows shown in Figure 1) were the same as those used in Experiment 5 in the study by Han, Humphreys, and Chen (1999). Subjects were asked to detect arrows pointing down left or down right that might appear at the global or local levels. The amplitudes of early occipital ERP components were examined to see if there was an enhancement of the P1 to local relative to global targets.

Another issue addressed in the current experiment was the level at which global and local information interact. May, Gutierrez, and Harsin (1995) found that interference from the global level continued to impede local processing even when the global precedence effect was canceled. They argued that the interference derived from competition in response selection that occurred when incompatible global information arrived faster than information about local stimuli. Han and Chen (1996) and Han, Fan, et al. (1997, 1999) showed that the latencies of an anterior N2 and a parietal P3 were longer when stimuli at the global and local levels were in conflict. Incongruity between global and local levels also increased the amplitudes of the posterior N2. The interference effect on these ERP components was stronger for local than global targets. Proverbio et al. (1998) provided evidence that global and local information may interact at an even earlier stage. They found that an occipital N1 (peaking at about 115 ms poststimulus) exhibited lower amplitude to local targets when the global configuration was inconsistent with local targets. In contrast, the N1 to global targets was not affected by local configuration. These results suggest that global configuration and local element interact with each other at different stages, that is, from early sensory-perceptual processing to late target classification and identification.

Interactions between global and local processing are also evident when targets are presented at both global and local levels simultaneously. For example, Miller (1981) and Han, Humphreys, and Chen (1999) found that, under the condition that global responses were faster than local responses, response times were still faster when targets appeared at both levels. Miller argued that information about local and global levels becomes available to activate responses over nearly the same time intervals, even when global precedence is observed. The global and local information facilitate each other at the level of decision making and mutually activate the appropriate decision. Nevertheless, there is little direct evidence to indicate at which level the global and local information start to facilitate each other. In the current study, an additional condition was used in which a target appeared at both the global

and local levels of hierarchical patterns. Thus the physiological basis of this redundancy effect could be examined.

Level-repetition effects have also been found to export powerful influences on the processing of hierarchical stimuli. For example, Ward (1982) and Robertson (1996) found that response times were faster on trials in which the target occurred at the same (global or local) level on the preceding trial. This level-repetition effect is evident regardless of whether a global precedence or a local precedence occurs. The level-repetition effect could not be attributed to response or target repetition (Rafal & Robertson, 1995). Moreover, Lamb and Yund (1996) showed that the level-repetition effect was not affected by filtering low spatial frequencies via using contrast-balanced compound stimuli, indicating that biases in spatial frequency filtering were unlikely to play a role (though see Robertson, 1996). Ward (1982) proposed that when targets appear at the same level on two successive trials, the attentional frame size (i.e., size of attentional "spotlight," Eriksen & Yeh, 1985; Treisman, 1982; Treisman & Gelade, 1980) need not change. However, when targets appear at different levels on two successive trials, subjects have to adjust the attentional frame to the correct size for the required identification, and this adjustment requires additional time. However, the notion based on variation of attentional spotlight is space based, and fails to account for level-repetition effects that can occur for two successive trials at different locations in the visual field (Lamb & Yund, 1996; Rafal & Robertson, 1995). To our knowledge, there has been little research studying the level-repetition effect in hierarchical processing using ERPs. Whether sensory-perceptual mechanisms contribute to the level-repetition effect in hierarchical processing was investigated in the present study by examining how the target-level repetition influences ERP components.

Methods

Participants

Fourteen healthy college students (3 women, 11 men; all right handed; aged between 19 and 27 years) participated in this experiment as paid volunteers. All had normal or corrected-to-normal vision. Informed consent was obtained before the experiment began.

Stimuli

Hierarchical stimuli were presented on a computer-controlled video monitor placed 60 cm from the subjects, as illustrated in Figure 1. Each of the stimuli, which were white on a black background, consisted of a global arrow made up of local arrows pointing in either of four directions (i.e., down left, down right, up left, or up right). The directions of the local arrows were either consistent or inconsistent with the direction of the global arrows. The local arrows were arranged in an 8×8 matrix. The global and local arrows subtended an angle of $4.1 \times 4.8^\circ$ and $0.38 \times 0.48^\circ$, respectively. The background had a luminance of 0.02 cd/m^2 . The compound patterns had a luminance of 0.68 cd/m^2 (with CIE coordinates of 0.237/0.285) at the viewing distance.

Procedure

Trials began with a centrally located white cross as fixation, which subtended $0.2 \times 0.2^\circ$ of visual angle, and was overlapped by the stimulus display, which was presented for a duration of 400 ms. The fixation remained illuminated during the interstimulus interval, which ranged from 1,000 to 1,400 ms. Subjects were asked to detect the presence of an arrow pointing down left or down right at the global, local, or both levels while scalp potentials were

recorded. Subjects pressed one of two keys on a pad with the right-hand thumb if targets were present and pressed another key with the left-hand thumb if targets were absent. The relation between targets and responding thumb was counterbalanced across subjects. Instruction placed an emphasis on accuracy. After 88 practice trials, a total of 2,000 trials in 20 blocks were presented. The probability of a target appearing on the global level, the local level, or both levels was equal (20%). The target was absent on 40% of the trials.

ERP Recording and Data Analysis

Electroencephalographic (EEG) activity was recorded from International 10/20 system sites FP1, FP2, F3, F4, F7, F8, T3, T4, C3, C4, T5, T6, P3, P4, O1, O2, Fz, Cz, Pz, and five other pairs of nonstandard sites. These other locations were: left (FC1) and right (FC2) sites located halfway between Cz and F3, and between Cz and F4, respectively; left (CP1) and right (CP2) sites located halfway between Pz and C3, and between Pz and C4, respectively; left (TO1) and right (TO2) sites located halfway between O1 and the midpoint between P3 and T5, and between O2 and the midpoint between P4 and T6, respectively; left (IN3) and right (IN4) sites located at the edge of the cap, equidistant from O1 and T5 and from O2 and T6, respectively; middle occipital sites posterior INz located at the posterior edge of the cap and anterior IPz located halfway between Pz and INz. The distance between INz and Pz was about 12.0 cm, and the distance between IN3 (or IN4) and the midpoint of distance connecting O1 (or O2) and T5 (or T6) was about 4.0 cm. The skin resistance of each electrode was less than 5 k Ω .

The algebraically computed average of the left and right mastoids was used as reference. EEG was amplified by using a band-pass of 0.1–40 Hz (1/2 amplitude cut-offs) digitized online at a sampling rate of 256 samples per second. Eye blinks were monitored with an electrode located below the right eye. The horizontal electrooculogram (EOG) was recorded from electrodes placed about 1.5 cm lateral to the left and right external canthi to measure eye movements. The ERPs were averaged offline using a computer program that extracted epochs of EEG beginning 200 ms before stimulus onset and continuing for 1,000 ms. Trials containing eye blinks, eye movements, muscle potentials exceeding a peak-to-peak threshold of 160 μV at any electrode, or incorrect behavioral responses were excluded prior to averaging. The ERP data were subject to two different analyses. To study the effect of hierarchical processing ERPs were compared for the global target, local target, both-level target, and nontarget conditions. To study level-repetition effects ERPs were computed separately for global targets preceded by global or local targets and for local targets preceded by global or local targets. The P1, N1, and posterior N2 were measured and analyzed at parietal, temporal, and occipital sites including P3, P4, T5, T6, O1, O2, TO1, TO2, IN3, IN4, IPz, and Pz. The P2 and anterior N2 were measured and analyzed at frontal and central sites including F3, F4, FC1, FC2, C3, and C4. The P3 was measured and analyzed at central, parietal, and occipital sites including Pz, P3, P4, C3, and C4. The baseline for these measures was the mean voltage of a 200-ms prestimulus interval and the latency was measured relative to the stimulus onset.

Reaction time (RT) and error rates were subjected to repeated-measures analyses of variance (ANOVA) with target level (targets appeared at the global, local, or both levels) as an independent variable. The error rates were transformed with an arcsine square-root function before statistical analysis. The peak latencies and amplitudes at each pair of electrodes were subjected to ANOVA

Table 1. Reaction Times (RTs) and Error Rates (%) in Each Condition

Target level	Local	Global	Both	None
RTs (ms)	504	473	433	496
Error rates (%)	6.7	4.4	2.6	6.9

Note: $n = 14$.

with target level and hemisphere (electrodes on the left or right hemisphere) as independent variables.

Results

Behavioral Measures

Target level effect. RTs and error rates in each condition are shown in Table 1. There was a significant effect of target level, $F(2,26) = 32.52, p < .0005$. Planned comparisons indicated that responses to targets presented at both levels were faster than those to global targets, $F(1,13) = 37.07, p < .0005$, which in turn were faster than responses to local targets, $F(1,13) = 7.58, p < .016$. Target error rates showed a similar pattern. The main effect of target level was significant, $F(2,26) = 24.26, p < .0005$. Planned comparisons confirmed that there were more errors in responses to local than global targets, $F(1,13) = 12.13, p < .004$, and there were fewer errors in responses to both-level targets than to global targets, $F(1,13) = 13.58, p < .003$. There was no indication of a speed-accuracy tradeoff.

Repetition effect. A 2×2 ANOVA was performed to verify the level-repetition effect of switching from one target level to another target level between trials. This analysis included target level on trial N (global or local) and target level on trial $N - 1$ (global or local) as independent variables. Figure 2 shows RTs and error rates as a function of target level on trials N and $N - 1$. There was a significant main effect of target level on RTs for trial N , $F(1,13) = 11.77, p < .005$, and a significant interaction between target level on trial N and target level on trial $N - 1$, $F(1,13) = 29.20, p < .0005$.

.0005. Planned comparisons confirmed that RTs to global targets preceded by global targets were shorter than those preceded by local targets (by an average of 46 ms), $F(1,13) = 36.31, p < .0005$. Similarly, RTs to local targets preceded by local targets were shorter than those preceded by global targets (by an average of 41 ms), $F(1,13) = 15.27, p < .002$. The ANOVA on error rates showed a similar pattern of significant effects of target level on trial N , $F(1,13) = 11.63, p < .005$, and a reliable interaction between target level on trial N and target level on trial $N - 1$, $F(1,13) = 21.74, p < .0005$. Planned comparisons indicated that there were fewer errors in responses to global targets preceded by global than by local targets, $F(1,13) = 11.89, p < .004$, and fewer errors in responses to local targets preceded by local than by global targets, $F(1,13) = 19.32, p < .0005$.

Electrophysiological Data

Grand-averaged ERPs across 14 subjects were computed separately for global target, local target, both-level target, and nontarget stimuli (shown in Figure 3). The ERPs were characterized by sequences of peaks that varied in morphology according to scalp location. The hierarchical stimuli evoked a prominent positive deflection that peaked between 80 and 140 ms (P1) over occipitoparietal sites. This P1 was followed by a later negative deflection over the occipitotemporal sites between 130 to 210 ms (N1). The hierarchical stimuli also elicited a positive P2 peaking between 160 to 220 ms over central and frontal sites, a negative-going N2 peaking between 230 to 330 ms over frontal-central sites and occipitotemporal sites, and a positive P3 peaking between 300 to 700 ms over central-parietal sites. Voltage maps of brain activation related to each type of stimuli are shown in Figure 4.

Effect of Hierarchical Processing

The P1 amplitudes varied significantly as a function of target level, being greater for local targets than for global targets. There was also a difference between the P1 to global and both-level targets. The difference in P1 amplitudes between each pair of conditions was significant at parietal, temporal, and occipital electrodes (see Table 2). The P1 effect did not differ between electrodes over the left and right hemispheres ($p > .05$). There were significant effects of target level on P1 peak latencies, O1-O2: $F(2,26) =$

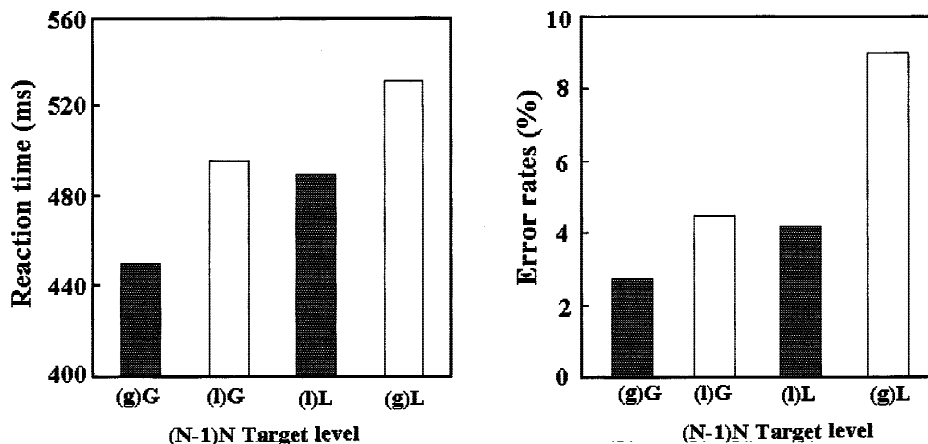
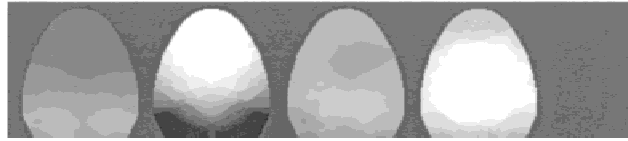


Figure 2. Mean reaction times and error rates for global and local targets on trial N as a function of target levels on the previous trial ($N - 1$). (g)G: global targets preceded by global targets; (l)G: global targets preceded by local targets; (l)L: local targets preceded by local targets; (g)L: local targets preceded by global targets.

9.46, $p < .001$; IN3-IN4: $F(2,26) = 7.96$, $p < .002$; and IPz: $F(2,26) = 7.31$, $p < .003$. Planned comparisons showed that the P1 latencies did not differ between the global and both-level target conditions ($p > .08$), whereas local targets evoked longer P1 latencies than global targets, 118 versus 112 ms at O1-O2: $F(1,13) = 6.71$, $p < .02$; 120 versus 114 ms at IPz: $F(1,13) = 9.03$, $p < .01$. The effect of hemisphere and its interaction with target level were

Both-level target



to show reliable differences between individual conditions ($p > .07$). There was no significant target level effect on the frontal-central P2 amplitudes and latencies.

The ANOVAs also showed reliable effect of target level on the posterior N2 peak amplitudes at temporal and occipital electrodes (see Table 3). The posterior N2 was more negative for local targets than for global targets, which in turn elicited enhanced N2s relative to both-level targets. The N2 effect did not differ between electrodes over the left and right hemispheres ($p > .1$). The ANOVA did not show any reliable effect of target level or hemisphere on the posterior N2 peak latencies. However, the main effect of target level was significant on the anterior N2 peak latencies at F3-F4, $F(2,26) = 5.85, p < .008$, and FC1-FC2, $F(2,26) = 3.74, p < .04$. Further planned comparisons showed that the anterior N2 peaked earlier in the both-level than global [F3-F4: $F(1,13) = 5.02, p <$

$.04$; FC1-FC2: $F(1,13) = 4.78, p < .045$] and local target conditions [F3-F4: $F(1,13) = 8.45, p < .01$; FC1-FC2: $F(1,13) = 4.93, p < .04$], but no difference was found between the global and local target conditions ($F < 1$).

There were significant main effects of target level on the peak amplitudes of the P3 component over the central and parietal sites. Planned comparisons showed that the P3 amplitudes in the both-level target conditions were higher than those in the global and local target conditions (see Table 4), but there was no difference between the global and local target conditions ($F < 1$). The P3 peak latencies showed a global advantage, being shorter for global than for local targets at central and parietal regions (see Table 5). The P3 latencies in the global and local target conditions were also longer than in the both-level target condition at central sites.

Table 3. Peak Amplitudes ($\pm SE$) (μV) of the Posterior N2 Component to Targets at the Global, Local, and Both Levels of Hierarchical Stimuli

Site	Target level			Target level effect		Planned comparisons			
	Both	Global	Local	F	p <	Global-both		Local-global	
						F	p <	F	p <
T5-T6	0.06 \pm .47	-0.54 \pm .45	-1.13 \pm .56	18.5	.0005	21.8	.0005	9.51	.009
TO1-TO2	1.27 \pm .50	0.41 \pm .49	-0.16 \pm .57	11.1	.0005	17.6	.001	3.76	ns
O1-O2	-0.01 \pm .38	-0.64 \pm .37	-1.13 \pm .42	8.46	.002	13.3	.003	3.47	ns
IN3-IN4	-1.36 \pm .33	-1.84 \pm .35	-2.22 \pm .41	7.83	.002	13.62	.003	3.03	ns

Note: n = 14. SE = standard error; ns = not significant.

Table 4. Peak Amplitudes ($\pm SE$) (μV) of the P3 Component to Targets at the Global, Local, and Both Levels of Hierarchical Stimuli

Site	Target level			Target level effect		Planned comparisons			
	Both	Global	Local	F	p <	Global-both		Local-both	
						F	p <	F	p <
C3-C4	8.81 \pm .67	7.54 \pm .66	8.04 \pm .70	6.89	.004	17.1	.001	5.09	.04
P3-P4	5.72 \pm .84	4.31 \pm .79	4.21 \pm .82	21.6	.0005	24.8	.0005	29.7	.0005
Pz	8.79 \pm .83	7.28 \pm .22	7.46 \pm .80	11.6	.0005	21.7	.0005	12.8	.004

Note: n = 14. SE = standard error.

Table 5. Peak Latencies ($\pm SE$) (ms) of the P3 Component to Targets at the Global, Local, and Both Levels of Hierarchical Stimuli

Site	Target level			Target level effect		Planned comparisons			
	Both	Global	Local	F	p <	Global-both		Local-global	
						F	p <	F	p <
C3-C4	411 \pm 11.9	422 \pm 20.2	492 \pm 27.8	14.6	.0005	6.36	.024	8.04	.01
P3-P4	389 \pm 15.6	395 \pm 18.1	422 \pm 24.9	4.18	.026	0.27	ns	6.79	.02
Pz	400 \pm 13.4	416 \pm 16.1	436 \pm 23.9	2.97	ns				

Note: n = 14. SE = standard error; ns = not significant.

Difference Waves

Target-specific difference waves were obtained by subtracting ERPs to nontargets from those to global, local, and both-level targets (shown in Figure 5). Voltage maps of the difference waves are shown in Figure 6. The earliest sign of global and both-level target selections were indexed by a negative deflection with a posterior distribution peaking at about 130 ms (Nd130), which was followed by another posterior negativity peaking at about 190 ms (Nd190). The ANOVA performed on Nd130 mean amplitudes between 110 and 140 ms showed greater amplitude for both-level than global targets, which in turn elicited higher amplitudes than local targets (see Table 6). The Nd130 exhibited an asymmetric distribution, being larger over the right than left hemisphere, P3-P4: $F(1, 13) =$

9.62, $p < .008$; O1-O2: $F(1, 13) = 6.57$, $p < .02$; TO1-TO2: $F(1, 13) = 5.15$, $p < .04$. However, there was no significant interaction between target level and hemisphere ($p > .2$). The Nd190 amplitudes showed a similar pattern as the Nd130, but planned comparisons performed on the mean amplitudes between 170 and 200 ms only confirmed higher amplitudes in both-level target than global target conditions at T5-T6, $F(1, 13) = 4.61$, $p < .05$. The amplitude of Nd190 was not different at electrodes over the left and right hemispheres ($F < 1$).

A broad negative component was particularly significant for local target selection, peaking at about 240 ms (Nd240) after sensory stimulation over the occipitotemporal regions. The voltage maps between 220 and 280 ms display a left hemisphere

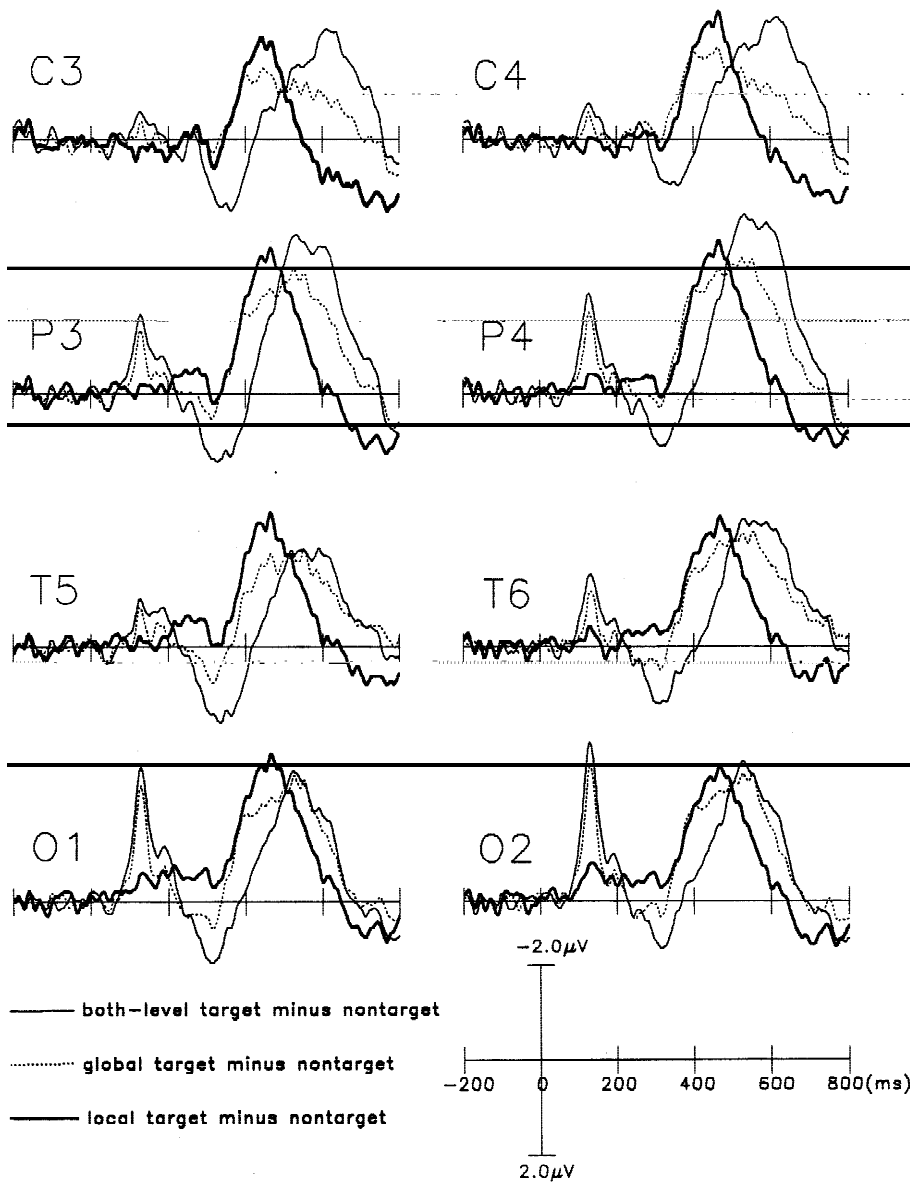



Figure 5. Difference waves for target selection obtained by subtracting event-related potentials to nontargets from those to global, local, and both-level targets.

distribution of the Nd240, though this asymmetry was not statistically significant ($F < 1$). Both-level target selection was also characterized by a selection positivity (SP) peaking at about 300 and 350 ms at the occipitotemporal and central sites, respectively. The focus of this SP related to both-level target selection started from the left temporal site, then moved to the central region. However, as can be seen in Figure 6, the SP focused over the left occipitotemporal sites for global target selection whereas it focused over the central-parietal region for local target selection. The mean amplitudes of the SP in the both-level condition was larger than those in the global target conditions at occipitotemporal sites between 250 and 350 ms, TO1-TO2: $F(1,13) = 18.2, p < .001$, and was larger than those in the local target condition at the central region between 290 and 340 ms, Cz: $F(1,13) = 6.27, p < .025$. Target selection was also characterized by a late broad negative component over the parietal region, reflecting P3 enhancement to nontargets in comparison with target stimuli.

Repetition Effect

To examine the repetition effect on ERPs, ERPs elicited by global and local targets were averaged in accordance with targets on the previous trial at the same or different level of hierarchical stimuli as that on the current trial. Grand-averaged ERPs to global and local targets preceded by targets appearing at the same or different levels are shown in Figures 7 and 8. A $2 \times 2 \times 2$ ANOVA was initially performed on ERP peak amplitudes with factors being current target level (global or local), previous target level (global or local), and electrode sites (left or right). The analysis of P1 amplitudes showed a small but significant interaction between current and previous target levels at O1-O2, $F(1,13) = 4.93, p < .043$, and significant interaction of Current Target Level \times Previous Target Level \times Electrode Sites at TO1-TO2, $F(1,13) = 5.92, p < .029$; and T5-T6, $F(1,13) = 5.12, p < .039$. A 2×2 ANOVA with previous target level and electrode sites as independent variables was then conducted on P1 amplitudes evoked separately by global and local targets. Interestingly, the results of the ANOVA showed

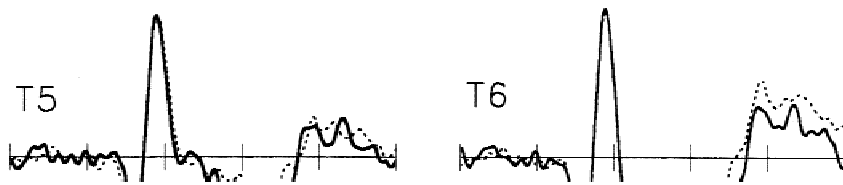


reliable main effect of previous target level on P1 amplitudes to local targets, O1-O2: $F(1,13) = 7.87, p < .014$; TO1-TO2: $F(1,13) = 10.2, p < .007$; and T5-T6: $F(1,13) = 7.36, p < .017$. The P1 amplitude to local targets was larger when preceded by global targets than when preceded by local targets. There was also a significant interaction between previous target level and electrode sites at TO1-TO2, $F(1,13) = 8.85, p < .01$, suggesting that the repetition effect on the P1 amplitude to local targets was greater on the right than on the left hemispheres. In contrast, similar analysis of P1 amplitudes evoked by global targets did not show any effect of previous target level ($F < 1$). The posterior N2 and parietal P3 to both global and local targets showed increasing

tendencies on trial N when preceded by targets at the same relative to different levels. However, these effects were not statistically reliable ($p > .05$).

Discussion

The goal of the current experiment was to study how selective processing of specific levels of hierarchically organized patterns modulates brain potentials. A divided attention procedure was used in which subjects were asked to identify targets that might appear at either global or local levels of hierarchical stimuli. The behavioral data replicated the results of previous work (Han, Hum-



phreys, & Chen, 1999; Miller, 1981) showing a global precedence effect. Responses to both-level targets were faster than those to global targets, which in turn were faster than those to local targets. The level-repetition effect was also evident for both global and local responses. Reaction times to target on trial N were faster and more accurate when targets were present at the same than different levels of hierarchical patterns on trial $N - 1$. This finding was consistent with the results of prior research using compound letters (Robertson, 1996; Ward, 1982).

It was evident that the ERPs varied reliably as a function of target levels in the hierarchical stimuli. The initial component modulated by hierarchical processing was the occipital P1, the peak amplitude of which was higher to local than global targets. The P1 exhibited longer peak latencies to local than global targets. These results provided evidence that hierarchical processing modulates activities in visual cortex at latencies as short as 110 ms, and thus corroborated the results of our prior work using the selective attention procedure (Han & Chen, 1996; Han, Fan, et al., 1997, 1999). The modulation of brain activities by hierarchical processing is manifested by a short-latency effect similar to that of spatial selective attention, with similar modulations seen whether attention is distributed evenly between global and local levels or is focused at one of the two levels.

Because a number of studies (Clark & Hillyard, 1996; Gomez et al., 1994; Heinze, Mangun, et al., 1994) have demonstrated that the P1 modulated by visual spatial attention is derived from the extrastriate cortex, the similar P1 modulations observed for hierarchical processing and spatial selective attention (Han et al., 2000) suggest that the hierarchical processing modulations arise in similar generators.

It is unclear why the P1 amplitudes differed between global and local target conditions. According to one hypothesis, the spotlight of spatial attention (Eriksen & Yeh, 1985) would be larger in the global than local conditions (Stöffer, 1994). Hence, there would be more local elements inside the attentional spotlight in global conditions. Because the P1 amplitude evoked by stimuli outside attentional spotlight is suppressed (Hillyard et al., 1995; Luck & Hillyard, 1995), more local elements inside the attentional spotlight in the global condition should evoke larger P1 amplitudes. However, our results conflict with this prediction. An alternative account is that, as the number of objects for identification is different between global and local target conditions (there is only one target for identification in the visual field in the global condition whereas there is more than one potential target for identification in the visual field in the local condition), an additional selection process may be required in the local condition (Han et al., 1999;

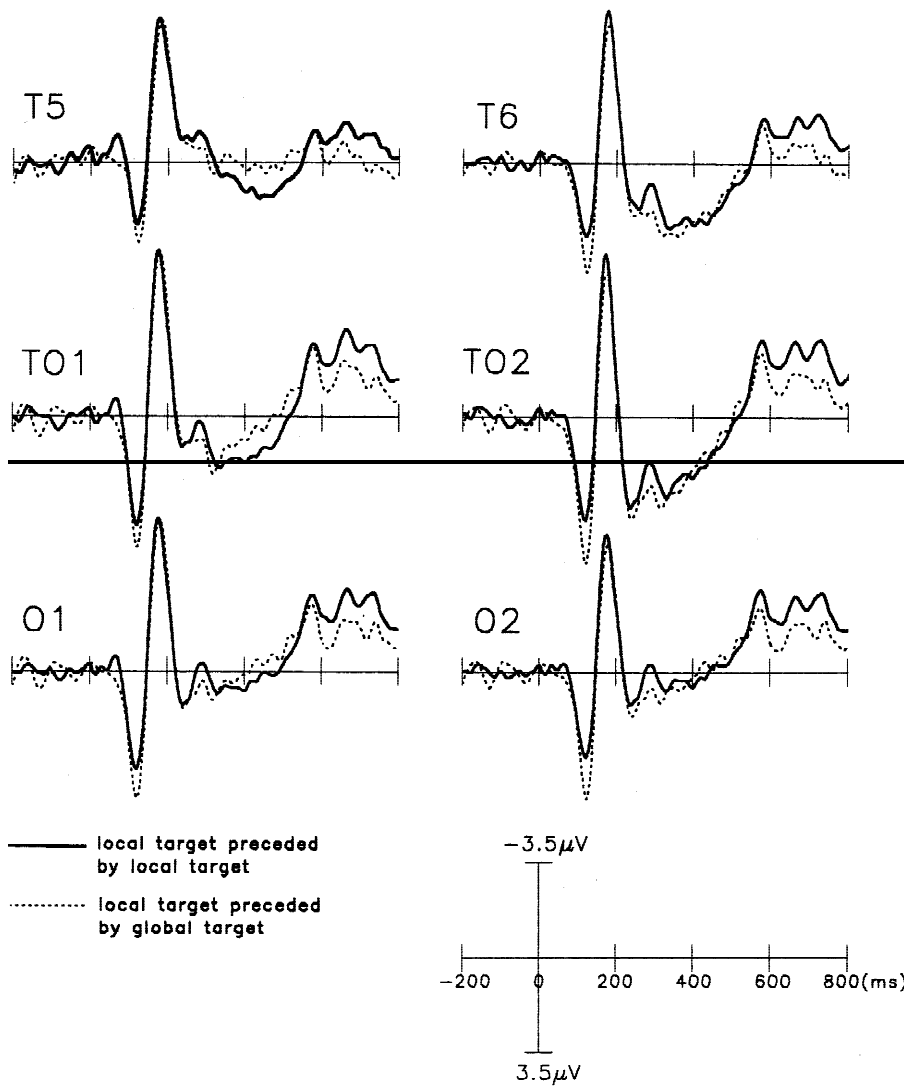


Figure 8. Grand-average event-related potentials to local targets as a function of target level on preceding trials.

Han & Humphreys, in preparation). Less selection effort in the global relative to local conditions may lead to decreased activities in the extrastriate cortex, and resulted in reduced P1 amplitude. Given that a global precedence effect was observed on ERP latencies and RTs, subjects may make responses to the both-level targets based on global information. Therefore selection of an individual local item may not be necessary for the both-level targets. For responses to nontargets, however, subjects had to examine both global and local levels of the stimulus, and thus the selection process would also be engaged in the nontarget condition. This analysis fits well with our results that the P1 amplitudes in the global and both-level target conditions were smaller than those in the local target and nontarget conditions. It also seems to account for the absence of P1 effects in other previous studies of hierarchical processing (Heinze et al., 1998; Heinze & Münte, 1993; Heinze, Münte, & Mangun, 1994; Proverbio et al., 1998). In Heinze et al.'s experiments the hierarchical patterns contained fewer local elements than those in Han et al.'s studies. Fewer local items may ease the selection of individual local elements and thus probably contribute to the disparity between the studies.

In line with the previous research, we also observed an N2 enhancement at temporal sites in local relative to global conditions. The effect of hierarchical processing on the posterior N2 did not distinguish between the left and right hemispheres. The symmetry of this N2 effect has been observed in previous studies using compound shapes (Han et al., 1997). However, this finding was at odds with the results of previous studies using compound letters (Han, Fan, et al., 1999; Heinze et al., 1998; Heinze, Münte, & Mangun, 1994), in which N2 enhancements in the local relative to global conditions are larger over the left than right hemispheres. Whether the posterior N2 effect is specific to compound letters needs to be examined in further research that recruits a same group of subjects and uses both compound shapes and compound letters.

Interestingly, the difference waves related to global target selection in this study displayed a different pattern in comparison with the results of previous work (Heinze & Münte, 1993; Heinze, Münte, et al., 1994; Heinze et al., 1998; Proverbio et al., 1998). We found that global target selection was first indexed by a selection negativity peaking at about 130 ms over the occipital visual cortex. Though this Nd130 was observed over both hemispheres, it was

larger at electrodes over the right than left hemispheres. Another selection negativity (i.e., Nd190) following Nd130 was observed over the occipitotemporal electrodes for global target selection that did not show any asymmetry. The first sign of local target selection, however, was a broad selection negativity (Nd240), which peaked much later than the global target selection-related Nd130 and appeared more prominent over the left occipitotemporal sites in voltage topographies. Fink, Halligan, Marshall, and Frith (1997) and Fink et al. (1996) found increases in relative regional cerebral blood flow (rCBF) in the right lingual gyrus when subjects named global letters, and increases in relative rCBF in the left inferior occipital cortex when subjects named local letters. However, PET studies provided little information about time courses of global and local processing in the two hemispheres. The difference waves in the current study showed a clear pattern of neural activities with high-resolution measures of the time course. The Nd130 indicated global target selection occurred at about 100 ms and was dominated by the right occipital cortex, whereas the Nd240 indicated that local target selection took place at about 200 ms and was dominated by the left occipitotemporal cortex. These data are consistent with previous ERP (Heinze, Münte, et al., 1994; Heinze et al., 1998) and lesion studies (Lamb et al., 1990; Robertson et al., 1988), and support the proposal that the right and left hemispheres dominate global and local target processing of hierarchical patterns respectively (although a reverse pattern is possible for processing of object-based hierarchical stimuli, see Fink, Marshall, et al., 1997). Moreover, the present ERP data indicated a separation in time course between the right and left hemispheres in hierarchical processing; global target selection may take place earlier than local target selection.

In addition, global target selection also elicited a selection positivity over the left occipitotemporal sites between 250 and 350 ms, and local target selection elicited a positivity between 280 and 340 ms, but focused over the central-parietal region. These findings suggest that there might be further separation between global and local processing after the initial global and local target selection. The left posterior brain may take part in global processing whereas the central-parietal region may take part in local processing. This proposal is in line with the previous ERP study (Han, Fan, et al., 1999), which found an anterior activity between 230 and 350 ms that was specific to local processing. Accordingly, it appears that there may be functional reorganization in the brain as hierarchical processing proceeds from the initial sensory-perceptual processing to the later stages.

The interaction between global and local processing was examined using redundant targets in the present study. ERPs to the both-level target showed a pattern similar to that in the global target condition. The differences in ERPs between the two conditions emerged at about 100 ms after sensory stimulus over the occipital cortex. There was a decrease of the P1 amplitude to both-level relative to global and local targets over the parietal, temporal, and occipital electrodes. The posterior N2 also showed lower amplitudes to both-level relative to global targets. Over the frontal-central region, however, the coexistence of targets at both global and local levels affected the anterior N2 peak latencies rather than peak amplitudes. The anterior N2 latencies in the both-level target condition were shorter than that in the global or local conditions. The early interaction between global and local information in the both-level target condition seemed to be indexed by a suppression of neural activities over the posterior cortex. The existence of a target on the local level in the both-level target condition made the posterior activities even more decreased in

comparison with those in the global target condition (we have shown a decrease of activity in the visual cortex to global relative to local targets). Over the frontal-central region, the interaction between global and local information was manifested as modulation of time courses of the processing. These results stand in agreement with studies using selective attention procedure (Han & Chen, 1996; Han et al., 1997). The late P3 component exhibited higher amplitude and shorter latency in the both-level than global target condition. As the P3 amplitude may reflect the confidence with which perceptual decisions are made (Kerkhof, & Uhlenbroek, 1981; Squires, Squires, & Hillyard, 1975) and the P3 latency is associated with processes of stimulus evaluation and categorization (McCarthy & Donchin, 1981; Mecklinger & Ullsperger, 1993; Mecklinger, Ullsperger, & Baldeweg, 1993), our P3 data suggest that, when targets appeared at both levels of hierarchical patterns, the process of stimulus evaluation and identification finished earlier and perceptual decisions were made with more confidence relative to when targets appeared only at global or local level.

The interaction between global and local processing was also reflected in the difference waves. Similar to global target selection, both-level target selection was also indexed by the Nd130 and Nd190 over the posterior cortex. However, the existence of local targets made these selection negativities enlarged, suggesting that coexistence of global and local targets may enhance the process of target selection. The late SP in the both-level target condition included both components that were observed in global and local target conditions respectively, starting from the left occipitotemporal sites and then extending to the central-parietal region. Thus it appears that, at this late stage, both-level target selection is characterized by summation of neural activities involved in both global and local target selections. Taken together, our ERP data indicate that the interaction between global and local information occurs as early as sensory-perceptual processing and continues to later stages of response execution.

The level-repetition effect shown in the behavioral data was approximately equal for global and local responses (46 vs. 41 ms), akin to the results of previous studies (Robertson, 1996; Ward, 1982). Interestingly, the level-repetition effect was also observed in the early posterior ERP component, but only in the local target condition. The P1 amplitude to local targets was enhanced when local targets were preceded by global targets. It is possible that global target selection at trial N-1 might have boosted global bias at trial N. This would lead to an enhanced effort to invoke the selection process of individual local elements, and produce a further enhancement in the P1 amplitudes. These ERP findings first indicate that an early sensory-perceptual mechanism may engage in the level-repetition effect. Moreover, this early sensory-perceptual mechanism may be different from that at a late stage of response selection and execution because level repetition only affected the P1 evoked by local targets but not by global targets, whereas RTs showed level-repetition effects for both global and local targets. In addition, we found evidence that the level-repetition effect on the P1 amplitude was larger on the right hemisphere than on the left. This is expected, given that the right hemisphere dominates global processing at the early sensory-perceptual stage and thus may produce a larger effect on local processing than the left hemisphere would.

The proposals that the size of an attentional spotlight or spatial frequency information was carried over from one trial to the next were not successful in accounting for the level-repetition effect in hierarchical processing. Lamb and Yund (1996) suggested that there may be a level-specific mechanism (rather than level-specific

information) that is “primed” by level repetition. Such a level-specific “mechanism” should be independent of representation of target features such as location, shape, and spatial frequency. In a study to examine level-repetition effect, Robertson (1996) presented two interesting findings. One was that the level-repetition effect took place even when the intervals between two successive stimuli were as long as 3 seconds. Another was that the level-repetition effect was eliminated when the parsing of global/local levels could not be conducted on the basis of spatial frequency differences between the two levels on the preceding trial. The latter result was demonstrated using two types of compound stimuli. The dark stimuli consisted of black compound letters (containing both high and low spatial frequency components). The contrast-balanced stimuli consisted of compound letters made up of contrast-balanced dots (low spatial frequency contents in the image were removed). No level-repetition effect was found when dark stimuli were preceded by contrast-balanced stimuli or vice versa. Because there has been no evidence that neuronal responses to different spatial frequency values persist as long as 3 second after stimulus offset, Robertson argued against the hypothesis that the level-repetition effect results from transfer of spatial frequency information over successive trials. Robertson proposed a model in which spatial frequency information used to parse global and local structures interacted with attentional weights assigned to spatially filtered channels. For example, when a target appears on the global level on trial $N - 1$, attentional weights assigned to low spatial frequencies are increased. If a target also appears on the global level on trial N , the attentional weights facilitate processing. In contrast, if a target appears on the local level on trial N , the attentional weights must be changed and accordingly result in slowed response times.

It appears that the mechanisms in the Robertson (1996) model avoid the assumption of delivering spatial frequency information between two successive trials. However, the model does not easily

account for the present ERP findings. Previous ERP studies have shown that attention to spatial frequencies is associated with a broad negative wave with onset latencies of approximately 175 ms and peak latencies of approximately 225–250 ms (Harter, Aine, & Schroeder, 1982; Harter & Previc, 1978; Previc & Harter, 1982). Attention to specific spatial frequency does not modulate the P1 component. Thus, it is unlikely that the level-repetition effect on the P1 amplitude to local targets observed here could be attributed to attentional weighting of different spatial frequencies. In addition, Robertson’s model did not distinguish between the level-repetition effects on responses to global and local targets, and thus could not accommodate the asymmetry of level-repetition effect on the P1 amplitude to global and local targets observed here. Therefore, the current ERP findings seemed to lend little support to the model based on attentional weights assigned to spatial frequency channels. We suggest that a model concerning the mechanisms of level-repetition effect in hierarchical processing must consider the symmetric effect on response times as well as the asymmetric effect on early ERP components.

Conclusions

The present results have shown that hierarchical processing and level repetition produced a series of effects starting from the early sensory-perceptual process to the late response selection and execution. The global and local processing began to interact with each other at an early level of sensory-perceptual processing and target selection. Early sensory-perceptual mechanisms may also contribute to the level-repetition effect, and were different for early global and local processes. New theories of hierarchical processing and level-repetition effect are needed to account for these ERP findings.

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