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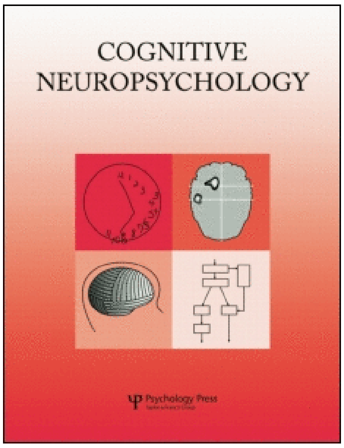

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Event-related potential evidence for a dual-locus model of global/local processing

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Event-related potential evidence for a dual-locus model of global/local processing

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We investigated the perceptual time course of global/local processing using event-related potentials (ERPs). Participants discriminated the global or local level of hierarchical letters of different sizes and densities. Participants were faster to discriminate the local level of large/sparse letters and the global level of small/dense letters. This was mirrored in early ERP components: The N1/N2 had smaller peak amplitudes when participants made discriminations at the level that took precedence. Only global discriminations for large/sparse letters led to amplitude enhancement of the later P3 component, suggesting that additional attention-demanding processes are involved in discriminating the global level of these stimuli. Our findings suggest a dual-locus time course for global/local processing: (a) Level precedence occurs early in visual processing; (b) extra processing is required at a later stage, but only for global discriminations of large, sparse, stimuli, which may require additional attentional resources for active grouping.

Keywords: Global/local processing; Event-related potentials; Hierarchical stimuli; Attention.

Our visual world is composed of an endless hierarchy of stimuli. Scenes are made up of objects, objects are made up of parts, and those parts are made up of features. To accommodate this hierarchy, the visual system is designed to engage the world at multiple levels and to shift flexibly from one level to another: We can admire a forest at a global level, or shift our awareness to a single tree at a more local level.

The dominant tool for investigating global/local processing in the laboratory has been hierarchical letter stimuli, which consist of a large, global letter, made up of several repetitions of a local letter (e.g., Figure 1; Navon, 1977). This stimulus has allowed for some of the key questions regarding global/local processing to be addressed behaviourally. For example, manipulation of stimulus parameters such as size (e.g., Kinchla & Wolfe, 1979) and density (i.e., spacing between local elements; Martin, 1979) have been shown to alter whether the global or local level of a stimulus appears to have a processing advantage, as indexed by reaction time (RT) measures (see Kimchi, 1992, for a review). Such data suggest

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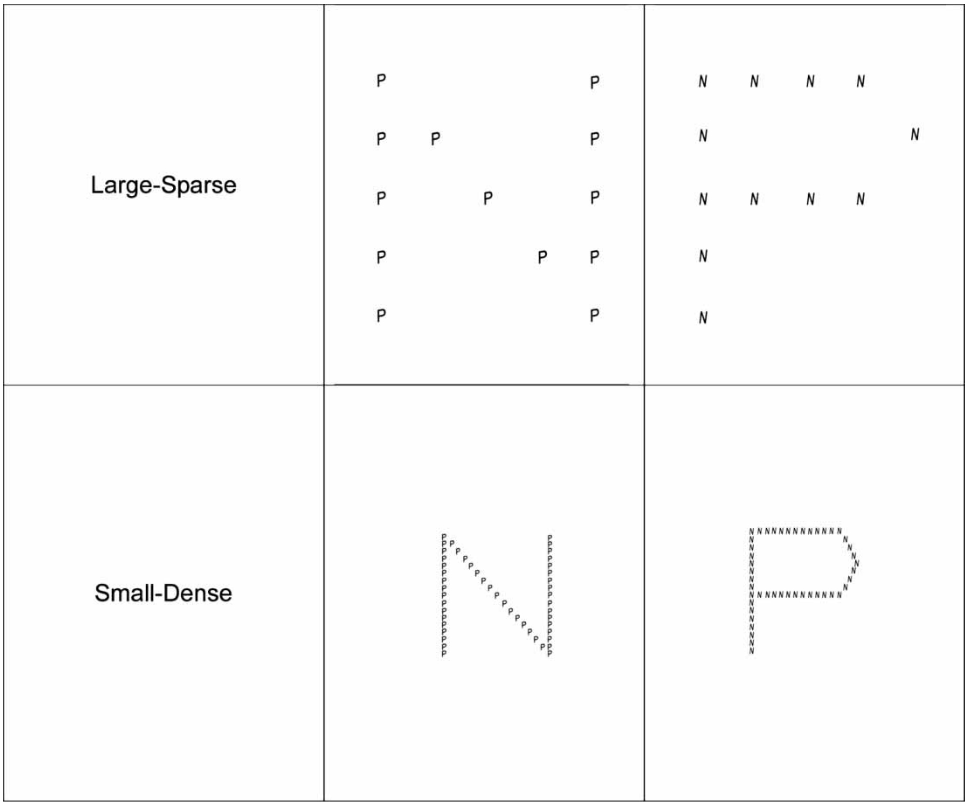


Figure 1. *Incongruent large/sparse and small/dense hierarchical letter stimuli.*

that stimulus configuration can in fact exert an influence on the balance between global- and local-level processing.

Taking a novel approach to this issue, Enns and Kingstone (1995) investigated the perceptual time course of processing at global and local levels using a visual search paradigm with hierarchical elements. They used this task because in visual search, perceptual and postperceptual processes are separable: The baseline measure of a distractor/reaction time cost function reflects perceptual processes that concern sensory, decision, and response factors, whereas the slope of the function represents postperceptual processes, primarily the RT cost of committing attention to the distracting items and the time-consuming process of integrating visual items to form a coherent object (Neisser, 1967; Sternberg, 1969; Treisman & Gelade, 1980). Enns and Kingstone created a hierarchical visual search task by asking participants to search among hierarchical objects for a target at either the global or the local level of one of the objects. The size and density of the hierarchical stimuli were manipulated. Enns and Kingstone reasoned that if only early, perceptual, factors were involved in the processing of hierarchical stimuli, RT differences between global and local tasks would only be reflected in baseline measures (i.e., because baseline represents perceptual processes). However, if later, postperceptual processes were involved differences should emerge in the slopes of the distractor/RT functions.

The results showed that with regard to baseline measures, the search for local-level items was faster for large and sparse stimuli, while global search patterns were faster for small and dense stimuli. This general pattern reflects the typical level precedence effect that occurs with traditional hierarchical stimuli (Kimchi, 1992). Inspection of the distractor/RT slopes revealed that local target detection was unaffected by stimulus size and density—that is, the slopes were flat. Interestingly, size and density had a tremendous effect on slopes for the global target detection task, with search for the global targets of large and sparse configurations generating steeper slopes than search for global targets of small and dense configurations. Thus Enns and Kingstone (1995) demonstrated that though both global and local target detection are reflected in the early baseline measures, global target detection seems to be modulated by the postperceptual attentional aspects of the task. In particular, as stimuli get larger and as interelement spacing increases, the later postperceptual demands of the global detection task increase. They proposed that this additional demand represents attentional grouping processes that are not required when grouping occurs automatically, as is the case for identifying the global level of small/dense stimuli, or when grouping is not necessary at all, as is typically the case for identifying local elements. Critically, Enns and Kingstone supported this conclusion by demonstrating that if they created a unique situation where grouping *is* required at the local level of a stimulus, local slope measures are affected. They concluded that collectively the data supported the interpretation that as displays become increasingly large and sparse, active attentional grouping is required for global-level processing.

While the conclusions of Enns and Kingstone (1995) are convincing from a behavioural standpoint, their inferences about the attentional demands of the task were drawn from indirect, behaviour-based measures of stimulus processing. Accordingly, our goal here was to reexamine the validity of this assumption by testing whether direct measures of cortical stimulus processing accord with the predictions of Enns and Kingstone. Specifically, we recorded event-related potentials (ERPs) from healthy participants while they made a forced-choice judgement about the identity of either the global or the local level of hierarchical letters. At issue was whether ERPs would show evidence that identifying the global level of widely spaced stimuli requires "active" attentional grouping processes, relative to global identification of small/dense stimuli and the identification of local elements.

Method

Participants

Participants ($n = 12$, 3 female) were all right-handed and ranged in age from 21 to 29 years (mean = 24.1 years). All had normal or corrected-to-normal vision. Participants received monetary compensation for their time and were tested under protocols approved by the Clinical Review Ethics Board of the University of British Columbia.

Stimuli and procedure

The same hierarchical stimuli as those used by Dalrymple, Kingstone, and Barton (2007) were used in this study, but only the extreme stimuli were chosen in attempts to elicit the strongest effects: large, sparse stimuli that elicited the slowest global-level reaction times, and small, dense stimuli that led to the fastest global-level reaction times in healthy participants (Figure 1). Upper-case global hierarchical letters N and P were created using repetitions of smaller upper-case letters N and P, creating 2 congruent letters and 2 incongruent letters. Global letters of two different configurations were constructed. Large/sparse global letters were made up of 12–13 local letters and measured approximately 12.5 × 13.5 degrees of visual angle. Adjacent local letters were separated by 2.5 degrees of visual angle. Small/dense global letters were made up of 47–49 local letters and measured approximately 4.0 × 4.5 degrees of visual angle. Adjacent local letters were separated by 0.01 degrees of visual angle. All letters were black on a white screen.

Participants were seated 57 cm in front of a 17″ computer monitor. Each task trial began with the onset of a black fixation dot at the centre of the screen. Between 2,700 and 2,900 ms after onset of fixation, a hierarchical letter appeared for 100 ms and was then replaced with a 300-ms

Table 1. *Reaction times as a function of stimulus configuration, congruency of global and local elements, and level of processing*

		Level of processing	
Configuration	*Congruency*	*Global*	*Local*
Small/dense	Congruent	489 (± 26.8)	530 (± 22.8)
	Incongruent	488 (± 25.2)	586 (± 23.2)
Large/sparse	Congruent	522 (± 30.5)	512 (± 28.4)
	Incongruent	565 (± 26.6)	526 (± 29.2)

Note: Reaction times (in ms) ± standard errors.

visual mask. This mask was replaced by the fixation dot in preparation for the next trial. The task was to discriminate the letter at the designated stimulus level (global or local) by button press on a video game controller. Participants performed all trials at one level before switching to the other, with the order counterbalanced between subjects. They were asked to respond as quickly and accurately as possible while behavioural performance was measured in terms of reaction time (Table 1) and accuracy of response (correct vs. incorrect). Trials were blocked by level (global or local) and configuration (small/dense or large/sparse). There were 10 trials for each of the four letter stimuli, resulting in 40 trials per block. Trials within each block were randomized. There were 5 blocks for each of the two letter configurations, and each block was performed for global- and local-level responses for a total of 20 blocks and 800 trials.

Electrophysiological recording

Scalp potentials were recorded from 24 tin electrodes that were evenly distributed across the scalp according to the standard 10–20 method of electrode placement and mounted in a custom elastic cap. All electroencephalographic (EEG) activity was recorded relative to the left mastoid, amplified (Grass Instruments, Model 12 Neurodata Acquisition System) with a band-pass of 0.1–30 Hz (1/2 amplitude cut-offs), and digitized online at a sampling rate of 256 samples per second. To ensure proper eye fixation, vertical and horizontal electro-oculograms (EOGs) were also recorded, the vertical EOG from an electrode inferior to the right eye, and the horizontal EOG from an electrode on the right outer canthus. All electrode impedances were kept below 5 kΩ. Offline, computerized artefact rejection was used to eliminate trials during which detectable eye movements (>1°), blinks, muscle potentials, or amplifier blocking occurred. Rejection itself was based on exceeded min–max difference thresholds within a −200- to 600-ms time window around each event (for eye and muscle artefacts), with each participant's threshold scaled via data visualization to the ambient level of that participant's EEG noise, or 50 contiguous data points with a constant voltage (for amplifier blocking). Following signal-averaging of the EEG, for each participant ERP waveforms were algebraically rereferenced to the average of the left and right mastoid signals and were filtered with a low-pass Gaussian filter (25.6-Hz half-amplitude cut-off) to eliminate high-frequency artefacts in the waveforms (for details on average number of trials rejected per condition, see below).

Results

When using hierarchical letter stimuli, the congruent condition presents the same letter at both the global and local levels, and thus it remains ambiguous on these trials as to whether the participant is actually responding to the target level of the stimulus. As a consequence, while initial omnibus analyses of both behavioural and ERP results includes congruency as a factor of interest, subsequent comparisons were planned a priori to specifically examine data from incongruent trials only.

Behaviour

Overall accuracy was at ceiling (99.14%), so this measure was not analysed further. All reaction times (RTs) are presented in Table 1. An omnibus repeated measures analysis of variance (ANOVA) was conducted with factors of congruency between global and local elements (congruent vs. incongruent), processing level (global vs. local target), and stimulus configuration (large/sparse vs. small/dense). This analysis revealed a significant main effect of stimulus congruency, $F(1, 11) = 19.79$, $p = .001$, indicating that overall RTs were longer on incongruent than on congruent trials, and a significant main effect of processing level, $F(1, 11) = 16.04$, $p = .002$, indicating that overall RTs were faster for global-level discriminations than for local-level discriminations. There were also two significant interactions. A two-way interaction between processing level and stimulus configuration, $F(1, 11) = 39.24$, $p < .0001$, indicated that while overall RTs were slower for the small/dense configuration in the local than in the global processing condition, overall RTs were slower for the large/sparse configuration in the global than in the local processing condition. A significant three-way interaction across all factors, $F(1, 11) = 46.91$, $p < .0001$, indicated that while there was a congruency effect at both levels of target processing for the large/sparse configuration, there was an absence of a congruency effect for the small/dense configuration at the global level of target processing.

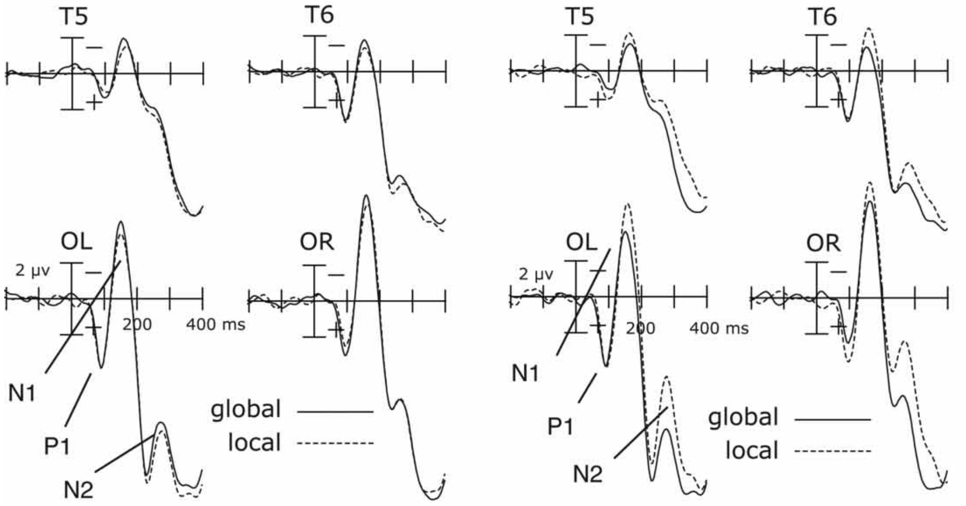
To examine the RTs specifically within the incongruent conditions, a second repeated measures ANOVA was performed with factors of processing level (global vs. local target) and stimulus configuration (large/sparse vs. small/dense). We found a significant main effect of processing level, $F(1, 11) = 30.51$, $p < .001$, with overall RTs being faster when discriminating the global level of the letter stimuli than when discriminating the local level. There was also a significant interaction between processing level and stimulus configuration, $F(1, 11) = 52.76$, $p < .001$, indicating that RTs were faster when discriminating the global level of small/dense letters, but faster when discriminating the local level of large/sparse letters. There was no effect of configuration, $F(1, 11) = 0.72$, $p = .41$. In sum these RT results confirmed that in the incongruent condition, the large/sparse stimuli produced a local-level processing bias, whereas the small/dense stimuli produced a global processing bias. Having established that these stimulus manipulations produced the desired behavioural effects, we next evaluated our ERP data.

ERPs

Analysis of the ERP data converged a priori on those visual components sensitive to attentional modulation: the lateral occipital P1, N1, N2, and the parieto-central midline P3 (see Coles & Rugg, 1995). The P1 amplitude typically increases with visual–spatial attention and reflects the magnitude or intensity of sensory-evoked responses in visual cortex (e.g., Mangun & Hillyard, 1991). In contrast, the N1 and N2 amplitudes positively correlate with perceptual difficulty (e.g., Senkowski & Herrmann, 2002; Vogel & Luck, 2000), and we therefore expected the amplitudes of these components to fluctuate with reaction times. Finally, the P3 has been identified as indexing the processing demands of a task, with modulations of the P3 thought to be related to postperceptual attentional allocation (e.g., Kramer & Strayer, 1988). If Enns and Kingstone's (1995) hypothesis is correct regarding active grouping, it predicts that this component should be specifically sensitive to the global processing demands of large/sparse stimuli.

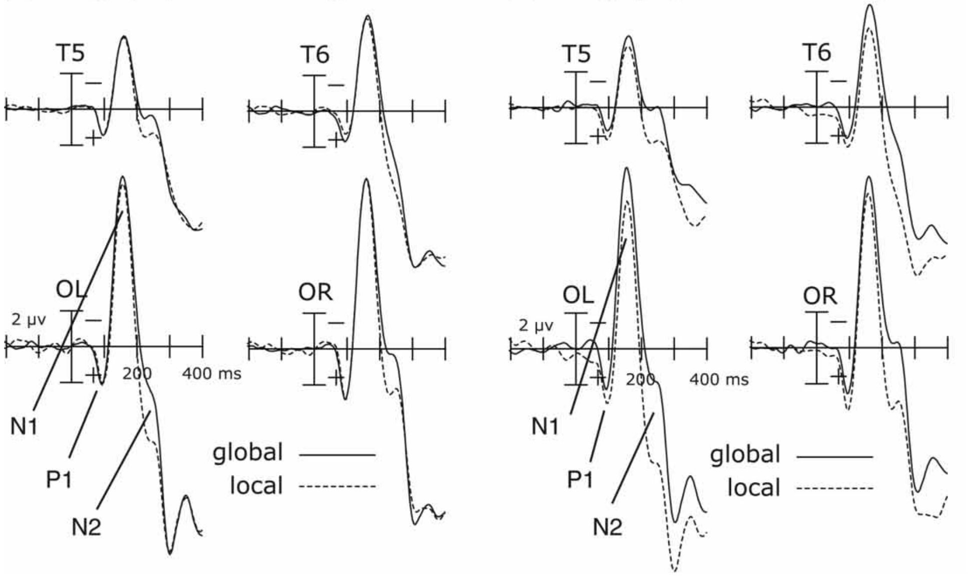
Statistical analyses of the P1 and N1 ERP data were based on peak amplitude measures taken at lateral occipital scalp sites T5/T6 and OL/OR (relative to a −200- to 0-ms prestimulus baseline), the scalp locations where the P1 and N1 have previously been shown to be maximal (e.g., Mangun & Hillyard, 1991). The latency of these components was first identified in the grand-averaged waveform for each electrode (T5/T6 and OL/OR) and condition of interest. For the data points entered into the ANOVA, the amplitudes of the single-subject waveforms were then measured within each electrode and condition at the corresponding peak latency identified in the grand-averaged waveform. Because the N2 component had a temporally broader effect at lateral occipital electrode sites T5/T6 and OL/OR than did the P1 and N1, this component was measured across all electrodes and conditions via a mean amplitude measure taken over a 50-ms time window beginning at 200 ms poststimulus. Likewise, the P3 was measured as a mean amplitude across a 375–575 poststimulus time window at midline electrode sites PZ and CZ, where the P3 (or P3b) is maximal (Coles & Rugg, 1995). All component measurements and waveform displays were scaled relative to a −200 to 0 prestimulus baseline.

Omnibus ANOVAs. The ERP waveforms for the P1, N1, and N2 components at lateral occipital electrode sites are shown in Figure 2, and the P3 waveforms at midline parietal/central sites are



(a) **Small/dense: congruent**

(b) **Small/dense: incongruent**



(c) **Large/sparse: congruent**

(d) **Large/sparse: incongruent**

Figure 2. *Group-averaged waveforms for P1, N1, and N2 event-related potential (ERP) components. Shown are data from lateral occipital-temporal sites OL/OR and T5/T6 as a function of stimulus configuration and congruency. In each plot the ERP responses are compared between whether the global or local level of the stimulus was processed.*

Table 2. *Peak P1 amplitude as a function of stimulus configuration, congruency of global and local elements, level of processing, and scalp electrode location*

			Electrode			
Configuration	*Congruency*	*Level*	*T5*	*OL*	*T6*	*OR*
Small/dense	Congruent	Global	1.31 (0.57)	3.73 (0.99)	2.63 (0.66)	3.00 (1.08)
		Local	1.52 (0.41)	3.47 (0.56)	2.27 (0.33)	3.04 (0.76)
	Incongruent	Global	1.03 (0.76)	3.75 (0.82)	2.73 (0.59)	2.48 (1.03)
		Local	1.54 (0.48)	3.94 (0.68)	2.58 (0.42)	3.53 (0.83)
Large/sparse	Congruent	Global	1.43 (0.45)	2.09 (0.66)	1.66 (0.35)	2.73 (0.73)
		Local	1.33 (0.48)	2.02 (0.80)	1.20 (0.43)	2.67 (0.71)
	Incongruent	Global	1.27 (0.43)	2.23 (0.96)	1.70 (0.49)	2.47 (0.77)
		Local	1.71 (0.50)	3.02 (0.83)	2.17 (0.29)	3.36 (0.84)

Note: Peak P1 amplitude (in μv) ± standard errors in parentheses.

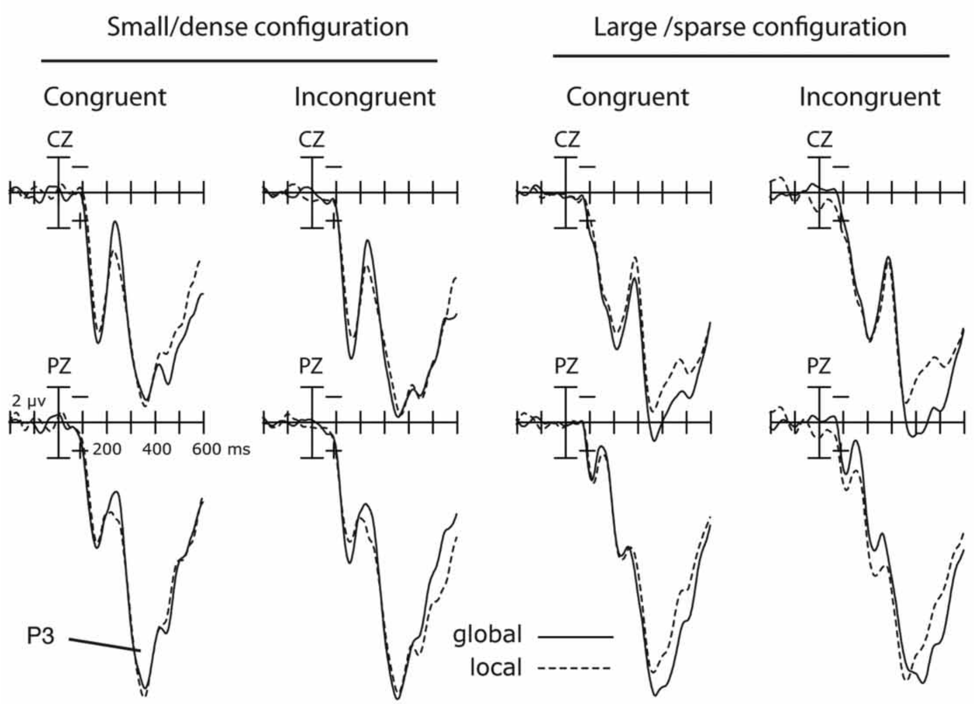
shown in Figure 3a, both as a function of stimulus configuration, congruency, and processing level. Within these waveforms, we first analysed each component separately via omnibus repeated measures ANOVAs that included our central factors of interest: stimulus configuration (small/dense vs. large/sparse), stimulus congruency (global and local letters congruent vs. incongruent), and target processing level (local vs. global target). For the P1, N1, and N2 components factors of electrode pair (OL/OR vs. T5/T6) and hemisphere of electrode site (left vs. right) were also included in the ERP analyses; for the P3, electrode site (PZ vs. CZ) was included as a factor. Notably, there were no systematic effects of these electrode-related factors in the analyses reported below, and thus for brevity and clarity we only include the stimulus- and task-related factors in our presentation of the statistical results. The effects reported below are highlighted in Figure 4 (for the P1, N1, and N2) and Figure 3b (for the P3), which plot the mean amplitudes of these ERP components as a function of stimulus configuration, target congruency, and processing level, collapsed across electrodes in the corresponding statistical analyses.

For the P1 (Table 2), there were no significant main effects or interactions across any of these factors, all Fs $(1, 11) < 2.38$, all ps $> .15$; as a consequence, no further considerations of the P1 data were made.

For the N1 (Table 3), a significant main effect of stimulus configuration was observed, $F(1, 11) = 24.16$, $p = .0005$, indicating that overall peak N1 amplitudes were greater for the large/sparse than for the small/dense stimuli. There was also a significant three-way interaction between configuration, congruency, and processing level, $F(1, 11) = 33.61$, $p = .0001$, indicating that while both stimulus configurations manifest an effect of processing level in the incongruent but not congruent conditions, the effect of processing level went in opposite directions: For the large/sparse configuration, the peak N1 amplitude in the incongruent condition was greater when processing targets at the global than at the local level, while for the small/dense configuration, the peak N1 amplitude in the incongruent condition was greater when processing targets at the local than at the global level.

For the N2 (Table 4), there was significant two-way interaction between processing level and stimulus congruency, $F(1, 11) = 7.09$, $p = .022$, indicating that the mean amplitude of the N2 showed a greater effect of processing level in the incongruent than in the congruent stimulus conditions. There was also a significant two-way interaction between stimulus configuration and processing level, $F(1, 11) = 11.72$, $p < .0057$, indicating that the overall mean N2 amplitude was larger during global than during local processing for large/sparse stimuli, but was larger during

(a) **P3 waveforms**



(b) **Mean P3 amplitude**

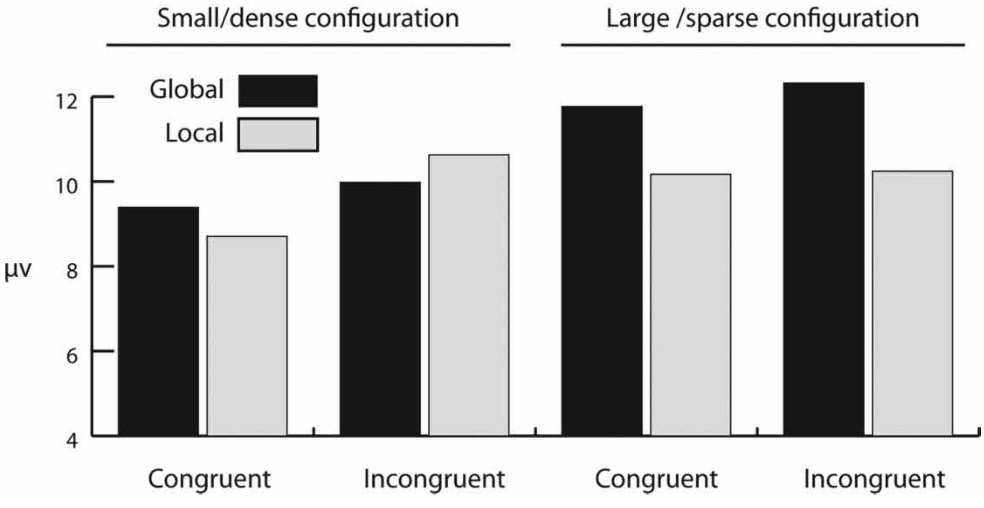


Figure 3. *P3 data. (a) The group-averaged waveforms for the P3 from midline parietal (PZ) and central (CZ) electrode sites, as a function of stimulus configuration and congruency. In each plot the ERP responses are compared between whether the global or local level of the stimulus was processed. (b) The mean amplitude of the P3 collapsed across CZ and PZ, as a function of stimulus configuration and congruency and whether the global or local level of the stimulus was processed. This plot highlights the effect of processing level for the large/sparse stimulus configuration only.*

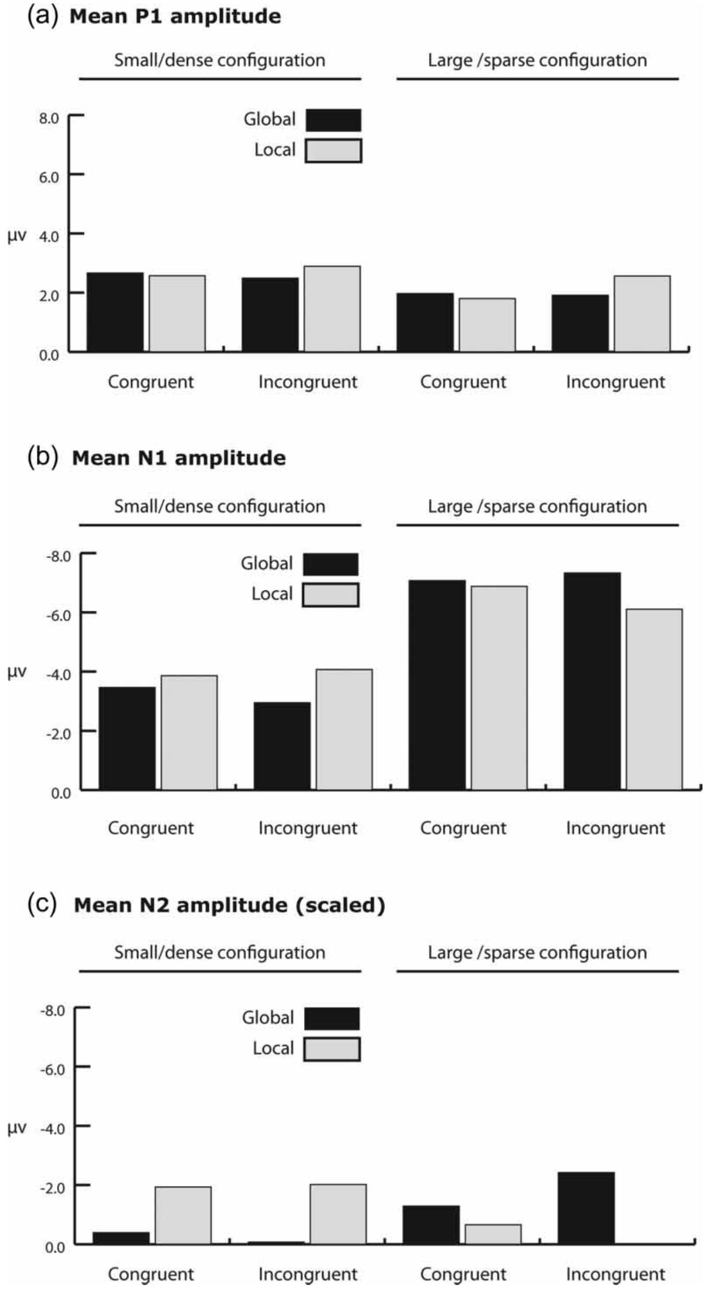


Figure 4. *The mean amplitudes of the P1, N1, and N2 components. Data are collapsed across lateral occipital electrode sites OL, OR, T5, and T6. These plots highlight that while there was no significant effects found in the P1 (a), the N1 (b) and N2 (c), both showed an increased amplitude when processing the local versus global level of the small/dense configuration (left), but an increased amplitude when processing the global versus local level of the large/sparse configuration (right). Note: The data for the N2 were normalized such that the smallest value (local processing of incongruent targets of the large/sparse configuration, far right) was set to 0, and all other values were scaled relative to this baseline. In this manner the magnitude of differences between conditions was preserved while allowing the data to be plotted such that increased bar height corresponds to a larger N2 amplitude.*

Table 3. *Peak N1 amplitude as a function of stimulus configuration, congruency of global and local elements, level of processing, and scalp electrode location*

			Electrode			
Configuration	*Congruency*	*Level*	*T5*	*OL*	*T6*	*OR*
Small/dense	Congruent	Global	−1.91 (1.63)	−4.30 (1.65)	−1.77 (1.21)	−5.86 (1.77)
		Local	−1.97 (1.62)	−4.81 (1.68)	−1.95 (1.29)	−6.73 (1.84)
	Incongruent	Global	−1.47 (1.58)	−3.62 (1.70)	−1.32 (1.24)	−5.40 (1.79)
		Local	−2.10 (1.63)	−5.13 (1.71)	−2.63 (1.27)	−6.43 (2.02)
Large/sparse	Congruent	Global	−4.05 (1.68)	−9.45 (2.68)	−5.31 (1.75)	−9.48 (2.15)
		Local	−3.99 (1.48)	−9.03 (2.56)	−5.16 (1.70)	−9.35 (2.06)
	Incongruent	Global	−3.96 (1.60)	−10.10 (2.92)	−5.73 (1.98)	−9.54 (2.16)
		Local	−3.43 (1.56)	−8.16 (2.62)	−4.38 (1.72)	−8.50 (2.13)

Note: Peak N1 amplitude (in μv) ± standard errors in parentheses.

local than during global processing for small/dense stimuli. Finally, there was a three-way interaction between configuration, congruency, and processing level, $F(1, 11) = 17.31$, $p = .0016$, such that the effect of processing level extended to both the congruent and incongruent conditions for the large/sparse stimuli, but was limited to the incongruent only condition for the small/dense stimuli.

For the P3 (Table 5), there was a significant main effect of congruency, $F(1, 11) = 26.28$, $p = .0003$, indicating an overall larger P3 amplitude for incongruent than for congruent trials. There was also a significant two-way interaction between stimulus configuration and processing level, $F(1, 11) = 6.77$, $p = .0246$, suggesting that while the P3 was larger in amplitude during global than during local processing for the large/sparse configuration, this effect was diminished/absent for the small/dense configuration.

Based on these initial omnibus results, we wanted to then examine the specific pattern of effects underlying the significant three-way interactions observed in both the N1 and N2 components. In particular, we wanted to determine whether the effects were consistent with increased perceptual/discriminative difficulty when discriminating the small/dense letters at a local level and the large/sparse letters at a global level. Likewise, we also wanted to examine the two-way interaction observed in the P3 component in order to confirm whether there was an effect of

Table 4. *Mean N2 amplitude as a function of stimulus configuration, congruency of global and local elements, level of processing, and scalp electrode location*

			Electrode			
Configuration	*Congruency*	*Level*	*T5*	*OL*	*T6*	*OR*
Small/dense	Congruent	Global	2.96 (0.97)	7.27 (1.72)	6.61 (1.02)	6.09 (1.77)
		Local	1.92 (0.90)	5.75 (1.39)	5.79 (0.92)	2.88 (1.49)
	Incongruent	Global	3.32 (1.04)	7.90 (1.86)	6.43 (1.08)	6.11 (1.68)
		Local	2.07 (1.05)	5.38 (0.94)	5.53 (0.94)	3.01 (1.49)
Large/sparse	Congruent	Global	2.02 (1.12)	6.86 (1.26)	5.65 (0.92)	4.35 (1.65)
		Local	2.24 (0.89)	8.06 (1.67)	6.44 (1.21)	4.66 (1.51)
	Incongruent	Global	1.48 (1.00)	5.33 (1.27)	4.48 (0.80)	3.09 (1.57)
		Local	2.46 (0.94)	9.09 (1.66)	7.26 (1.16)	5.23 (1.57)

Note: Mean N2 amplitude (in μv) ± standard errors in parentheses. Mean amplitude was measured over a 200–250 time window poststimulus.

Table 5. *Mean P3 amplitude as a function of stimulus configuration, congruency of global and local elements, level of processing, and scalp electrode location*

			Electrode	
Configuration	*Congruency*	*Level*	*PZ*	*CZ*
Small/dense	Congruent	Global	9.66 (1.32)	9.12 (1.48)
		Local	9.48 (1.22)	7.95 (1.25)
	Incongruent	Global	10.00 (1.57)	9.96 (1.61)
		Local	11.34 (1.47)	9.92 (1.57)
Large/sparse	Congruent	Global	11.96 (1.56)	11.57 (1.84)
		Local	10.21 (1.52)	10.12 (1.64)
	Incongruent	Global	12.41 (1.65)	12.24 (1.99)
		Local	10.67 (1.34)	9.80 (1.34)

Note: Mean P3 amplitude (in μv) ± standard errors in parentheses. Mean amplitude was measured over a 375–575 time window poststimulus.

processing level for the large/sparse stimulus configuration but not the small/dense configuration. Accordingly, we thus performed separate statistical analyses on the N1, N2, and P3 within each of the two stimulus configuration levels.

ERPs: Small/dense configuration. Repeated measures ANOVAs were performed on the N1, N2, and P3 components generated by the small/dense letters that included factors of congruency (global and local letters congruent vs. incongruent) and processing level (local vs. global target). For the N1, there was a significant interaction between stimulus congruency and processing level, $F(1, 11) = 16.13$, $p = .002$, such that the peak N1 amplitude was greater in the incongruent condition when processing targets at the local than at the global level. For the N2, there was a main effect of processing level, $F(1, 11) = 9.55$, $p = .01$, indicating that the mean amplitude of the N2 was consistently larger when processing targets at the local than at the global level, regardless of congruency condition. Taken together, these results were thus consistent with significant increases in N1 and N2 amplitude for the small/dense letters, specifically when performing a local discrimination with incongruent hierarchical letters. For the P3, while there was a significant main effect of congruency, $F(1, 11) = 12.37$, $p < .001$, indicating that the P3 amplitude was larger for incongruent than for congruent targets, and there was no main effect of processing level nor an interaction between congruency and processing level.

ERPs: Large/sparse configuration. Repeated measures ANOVAs were also performed on the N1, N2, and P3 components generated by the large/sparse letters, which included factors of congruency (global and local letters congruent vs. incongruent) and processing level (local vs. global target). For the N1, there was again a significant interaction between congruency and processing level, $F(1, 11) = 11.19$, $p = .007$, such that the peak N1 amplitude was greater in the incongruent condition when processing targets at the global than at the local level. For the N2, there was again a significant main effect of processing level, $F(1, 11) = 6.17$, $p = .03$, indicating that the mean amplitude of the N2 was consistently larger when processing targets at the global than at the local level, regardless of congruency condition. There was also a significant interaction between congruency and processing level, $F(1, 11) = 22.11$, $p = .0006$, revealing that this effect of processing level was greater under incongruent than under congruent target conditions. In short, these results were again consistent with significant increases in N1 and N2 amplitude for the large/sparse letters, specifically when performing a global discrimination with incongruent hierarchical stimuli. For the P3, there was a significant main effect of processing level, $F(1, 11) = 9.97$, $p = .0091$, but no main effect of congruency or an interaction between processing level and congruency.

ERPs: Direct comparison of incongruent conditions. The foregoing analyses converge on the conclusion that the significant interactions between processing level and congruency in N1 and N2 amplitude were specifically associated with incongruent trials. That is, the N1 and N2 appeared to systematically decrease in amplitude when processing (a) global relative to local letters in the incongruent condition of the small/dense configuration and (b) local relative to global letters in the incongruent condition of the large/sparse configuration. Given this differential direction of processing level effect between the two stimulus conditions, it predicted that for incongruent trials there should be a significant interaction in both the N1 and N2 between these two factors. To confirm this prediction, we analysed the N1 and N2 on incongruent trials only via repeated measures ANOVAs with factors of processing level (global vs. local) and stimulus configuration (small/dense vs. large/sparse). For the N1, we found a significant interaction between processing level and stimulus configuration, $F(1, 11) = 10.62$, $p = .008$; there was also a significant main effect of stimulus configuration, $F(1, 11) = 24.02$, $p < .001$. The interaction was further investigated with separate one-way ANOVAs for large/sparse and small/dense letters, respectively, with factor of processing level. For large/sparse letters there was a significant effect of processing level, $F(1, 11) = 8.16$, $p = .0156$, indicating that the N1 amplitudes were smaller for local- than for global-level discriminations. For small/dense letters there was a trend to significance, $F(1, 11) = 4.37$, $p = .0605$, indicating that the N1 amplitudes were marginally smaller for the global-level than for the local-level discriminations.

For the N2 there was a significant interaction between processing level and stimulus configuration, $F(1, 11) = 15.87$, $p = .0021$. The interaction was further investigated with separate one-way ANOVAs for large/sparse and small/dense letters, respectively, with factor of processing level. For large/sparse letters there was a significant effect of processing level, $F(1, 11) = 11.13$, $p = .0066$, indicating that the N2 amplitudes were smaller for local- than for global-level discriminations. For small/dense letters there was also a significant effect of processing level, $F(1, 11) = 11.95$, $p = .0054$, indicating that the N2 amplitudes were smaller for the global-level than for the local-level discriminations.

Together, these results indicate that there is indeed a systematic decrease in amplitude for these components for the local relative to global letters in the incongruent condition of the large/sparse configuration and, conversely, global relative to local letters in the incongruent condition of the small/dense configuration. This interaction parallels the RT data such that the decrease in amplitudes occurs for the conditions for which participants had the smaller RTs.

We performed similar analyses for the P3, again with factors of processing level and stimulus configuration. Here we found a significant interaction between processing level and stimulus configuration, $F(1, 11) = 7.42$, $p = .0198$. This interaction was further investigated with separate one-way ANOVAs for each configuration, with factor of processing level. While there was no effect of processing level for the small/dense configuration, $F(1, 11) = 0.60$, $p = .4553$, there was a significant effect of processing level for the large/sparse configuration, $F(1, 11) = 6.03$, $p = .032$, indicating that for large/sparse letters alone there was a larger P3 amplitude for global-level than for local-level discriminations.

Discussion

Our experiment was designed to investigate the perceptual time course of global/local processing and, in particular, to test the validity of the conclusion drawn by Enns and Kingstone (1995) that identifying the global level of widely spaced hierarchical stimuli requires greater "active" attentional grouping processes than either the global identification of small/dense stimuli or the identification of local elements. In this regard, we found two critical results. First, we found that modulations of the early N1 and N2 ERP components correlated with behavioural RT effects: N1/N2 amplitudes were smaller when processing the level of the stimulus that participants respond to more quickly. Specifically, there were smaller N1/N2 amplitudes when participants responded to (a) the local level of large/sparse stimuli and (b) the global level of small/dense stimuli.

Second, and more importantly, the amplitude of the later P3 component was selectively increased for global-level discriminations of large/sparse stimuli only, with larger peak amplitudes for global discriminations of these hard-to-group items than for global discriminations of small/dense stimuli, and any local-level discriminations. This result is again consistent with the behavioural results of Enns and Kingstone (1995). In particular, they showed that the baseline search times for both local and global targets are affected by size and density manipulations, while the distractor/RT slope is only affected by these manipulations for conditions where active grouping is required; for example, search for the global targets of large/sparse configurations generates a steeper slope than search for global targets of small/dense configurations. Enns and Kingstone proposed that the baseline measure for a visual search represents early, perceptual, processing of targets, while the distractor/RT slope represents later postperceptual processing relating to attention-mediated grouping. Thus, they suggest that while both global and local processing occur at an early stage (as also suggested by our N1/N2 data), active grouping requires additional later stage processing, which, in the present case, occurs when global discriminations are made about targets that are large and made up of widely spaced elements that need to be effortfully grouped into a coherent whole. Thus, Enns and Kingstone's conclusion precisely aligns with our finding here that P3 amplitude was selectively increased for these specific stimuli.

Our P3 findings are consistent with other ERP findings from experiments using hierarchical letters. For example, Volberg and Hübner (2004) found overall increased amplitudes of the P3 when participants responded to the global, compared to the local, level of hierarchical letters. Although it is difficult to make cross-study comparisons, the stimuli in the Volberg and Hübner experiment had larger interelement spacing than those used in our small/dense condition, suggesting the possibility that their stimuli, like our large/sparse stimuli, required active grouping to be processed at a global level. Also consistent with our results, Volberg and Hübner found that their effects were only present with incongruent stimuli, highlighting the fact that conflict between global and local levels are crucial for these effects. These authors suggest that when stimuli are congruent, letter identity alone can be processed. However, when stimuli are incongruent, target level must also be processed, leading to modulation of the P3 component with target level.

Given that the P3 has been identified as indexing postperceptual attentional allocation (e.g., Kramer & Strayer, 1988), it is possible that modulations of this component reflect other attentionally demanding processes beyond active grouping. One excellent suggestion is that the P3 reflects the active suppression of the more salient, but irrelevant, level of the stimulus (i.e., the local level of large/sparse stimuli when global judgements are made and the global level of small/dense stimuli when local judgements are made). If this were the case, one would predict modulation of the P3 much like the modulation seen here with the N1/N2 components—that is, an interaction between processing level and stimulus configuration such that there is an enhancement of the P3 component corresponding to judgements about the level that does not take precedence. While this possibility is extremely reasonable at a theoretical level, it is not supported by the current data set. We see no modulation of the P3 for judgements at either the global or the local level of small/dense (easy to group) stimuli, yet we do see an enhancement of the P3 for global judgements only for large/sparse stimuli (hard to group). Thus, while it is still possible that suppression of the more salient, but irrelevant, level of the stimulus is an active, attentionally demanding process, this proposal is not captured or reflected by the current ERP measures.[1]

It is worthwhile considering whether other hypotheses regarding the role of the P3 are supported by our results. Verleger, Jaskowski, and Wascher (2005) suggest that the P3b reflects a process of monitoring the transformation of a response decision into action. This possibility can be evaluated in light of the present results because our task requires participants to make a decision regarding the identity of the target letter and to transform that decision into an appropriate manual response (i.e., a button press). Our results show an enhancement of the P3 to global-level judgements of large/sparse stimuli alone. It is unclear why this condition would recruit monitoring of the transformation of stimulus classification to action while global-level judgements of small/dense stimuli, and local-level judgements in general, would not. Contrary to our results, Verleger et al.'s interpretation of the P3 would predict equal enhancement of the P3 regardless of target level or stimulus configuration. Thus a postperceptual attentional allocation account of the P3 component is still preferred in light of the present data.

These data not only speak to the perceptual time course of the processing of hierarchical stimuli in healthy participants, but also have implications for special neurological populations. Simultanagnosia is a rare neuropsychological disorder that results in a restriction of visual attention such that the patient is only aware of a single object at any one time (Moreaud, 2003; Rafal, 2003; Rizzo & Vecera, 2002), yet, paradoxically, patients are often unable to see single objects when those objects are made up of smaller local elements (Dalrymple et al., 2007; Karnath, Ferber, Rorden, & Driver, 2000).

Many behavioural studies have shown that hierarchical stimuli are not processed normally by patients with simultanagnosia, with patients processing only the local level of some stimuli (Clavagnier, Fruhmann Berger, Klockgether, Moskau, & Karnath, 2006; Dalrymple et al., 2007; Huberle & Karnath, 2006; Karnath et al., 2000; Shalev, Mevorach, & Humphreys, 2007). Previously this effect has been interpreted in terms of local-level processing: Some researchers have suggested that simultanagnosics are unable to process the global level of stimuli because they are "captured" by the local level of those stimuli (Karnath et al., 2000) or that patients may have trouble disengaging attention from the local elements in order to process the global level of the stimulus (Clavagnier et al., 2006). It is now clear that patients actually produce a fair amount of exploratory eye movements when viewing these stimuli and that a disengage deficit is unlikely (Clavagnier et al., 2006). Our data further this by suggesting that global processing itself may be disrupted due to the high attentional demands of active grouping.

What is the role of the local elements in grouping? With such a complex relationship between global and local processing, the local elements of these stimuli may influence the ease at which grouping occurs. For example, Shalev et al. (2007) found that familiarity with the local elements of hierarchical stimuli influenced global-level perception in simultanagnosic patient G.K. G.K. performed well at naming the global level of a familiar global shape (English letter) when he was unfamiliar with the local elements that made up that shape (Hebrew letters). However, when G.K. was trained to learn Hebrew letters such that the local elements were familiar to him, his performance on the global English letters declined. Thus while attentionally demanding global-level grouping may underlie the difficulties with global-level processing in simultanagnosia, grouping itself may be influenced by the identity or properties of the local components. Indeed, as Enns and Kingstone (1995) show, when grouping is required at the local level of the stimulus, attention is required there too.

In conclusion, our results support a dual-locus model of global/local processing. We show early modulation of the N1/N2 that mirrors behavioural reaction time and level precedence effects with

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[1] Thank you to L. Shalev for pointing out a second alternative interpretation of our results, that the P3 effect reflects the controlled spreading of attention across a large area. This is an interesting possibility for future research, which could be tested by comparing P3 modulation in response to our large/sparse stimuli to P3 modulation in response to new, large/dense, stimuli.

hierarchical stimuli. At a later stage of processing, the P3 component, which indexes postperceptual attentional allocation, shows an enhancement during active grouping of the global stimulus. These findings support the conclusions drawn by Enns and Kingstone (1995), that active grouping is an attentionally demanding process. These findings speak to visual processing in healthy participants, but also carry implications for neuropsychological populations; for instance, impaired grouping abilities may underlie the global-level processing deficit in patients with simultanagnosia because these grouping processes may place demands on an already limited attentional system.

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