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The time-course of global and local attentional guidance in Kanizsa-figure detection

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ABSTRACT

Object configurations can be perceptually represented at various hierarchical levels. For example, in visual search, global Kanizsa figures are detected efficiently, whereas search for local groupings is inefficient, with similarity-dependent nontarget interference arising at the hierarchical level that defines the target (Conci, Müller, & Elliott, 2007). The present study was designed to examine the electrophysiological correlates of this global–local search asymmetry. The results revealed differences between hierarchical object levels to be evident throughout a number of processing stages: search for a global, versus a local, target elicited larger amplitudes in early sensory components (P1, N1). Moreover, the efficiency of attentional orienting towards a target was mirrored in the Posterior Contralateral Negativity (PCN), with PCN latencies being substantially delayed (by ~70 ms) with local, versus global, targets. Finally, late components (P3 and slow wave—SW) reflected the overall search efficiency, which was determined by both the hierarchical level at which the target was defined and the similarity-based nontarget interference. Taken together, this pattern shows that multiple, sequential processes of object completion contribute to the attentional precedence of a globally bound object over a mere local element grouping.

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1. Introduction

Natural scenes typically consist of multiple objects that can be described at various, hierarchical levels of organization (or representation). For instance, a forest has trees, and the trees, in turn, have leaves. A similar hierarchical relationship between parts and wholes has also been demonstrated using a variety of composite figures. For example, the Navon letter (Navon, 1977) in Fig. 1A consists of a local arrangement of the letters "H", which combine to form the global letter "U". Similarly, Kanizsa figures (Kanizsa, 1976) comprise a local arrangement of "pacman"-type inducers. When the local inducers face inwards (see Fig. 1B), a salient, global figure (in the example, a square) emerges (referred to as an 'illusory figure'). By contrast, when the local inducers face outwards (see Fig. 1C), no corresponding global figure is induced. Both examples of groupings illustrated in Fig. 1B and C are in principle identical with regard to their physical stimulus attributes (i.e., with respect to the inducer elements or, respectively, the 'local' level of representation). However, only the Kanizsa figure gives rise to an illusory square, which can be considered a 'global' object representation (see Fig. 1 for an illustration of global and local object representations; see also Rauschenberger & Yantis, 2001). Thus, a variety of objects can be represented at multiple levels, with global properties being dependent on the existence and arrangement of more elementary local parts.

Also, generally, object information can be accessed at various hierarchical levels. However, the default level of attentional orienting has often been described in terms of "global precedence", illustrating that the 'forest comes before the trees' (Navon, 1977; Rauschenberger & Yantis, 2001; Rensink & Enns, 1995). For instance, Rensink and Enns (1995) demonstrated that visual search is based on the global level of representation that comprises integrated objects, while corresponding fragmentary (local) parts could not be accessed with comparable efficiency. In general agreement with this finding, Conci, Müller, and Elliott (2007) showed that hierarchical levels in Kanizsa figures give rise to a search asymmetry in favor of global precedence: search for a global Kanizsa square (Fig. 1B) was more efficient than search for a comparable local configuration (Fig. 1C; mean search reaction time (RT)/set size slopes were 16 and 46 ms/item, respectively). Consequently, detection of a global shape precedes detection of a configuration that is uniquely defined at a local hierarchical level (see also Conci, Müller, & Elliott, 2009, for a comparison of visual search for different types of global shape).

Moreover, the study of Conci et al. (2007) demonstrated that variations of target–nontarget similarity (cf. Duncan & Humphreys,



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Fig. 1. Examples of hierarchical stimulus configurations: (A) Navon letter, (B) Kanizsa square, (C) local grouping without global shape information, and (D) grouping with partial global shape information. Each stimulus configuration depicts a local configuration of inducers (bottom) together with a schematic illustration of the corresponding global object representation (top).

1989) were particularly effective at the search-critical hierarchical level at which the target was defined: in global search, detection of a Kanizsa square target was more efficient when the nontargets comprised local groupings (see Fig. 1C) rather than a partial global shape (see Fig. 1D; mean search slopes were 16 and 59 ms/item, respectively) - that is, the presence of global shape information in the nontarget configurations caused search interference. However, a comparable variation of the nontarget similarity in search for a local target grouping (see Fig. 1C) caused an even greater reduction of search efficiency: search was again relatively efficient when nontarget configurations were arranged such that none of their local inducers were oriented in the same direction as those of the target (as in Fig. 1B); however, massive search interference occurred when two (out of the four) local nontarget inducers were identical in orientation to the target (see Fig. 1D; mean search slopes were 46 and 189 ms/item, respectively). Taken together, this pattern of results demonstrates a search asymmetry: search efficiency is determined by the similarity between target and nontargets; however, the degree of search interference critically depends on the hierarchical level on which the target is specified.

Studies that investigated event-related potentials (ERPs) evoked by Kanizsa figures have primarily reported components associated with the emergence of a global shape. In (many of) these studies, typically, a global illusory figure has been compared to a control condition that presented a local-level configuration only (for examples, see Fig. 1B and C, respectively). Results revealed that the formation of a Kanizsa square is associated with an increase in the N1-amplitude peaking ~100-170 ms after stimulus onset relative to a baseline configuration without a global square (Brodeur, Lepore, & Debruille, 2006; Herrmann & Bosch, 2001; Herrmann, Mecklinger, & Pfeiffer, 1999; Martinez, Ramanathan, Foxe, Javitt, & Hillyard, 2007; Murray et al., 2002; Murray, Foxe, Javitt, & Foxe, 2004; Pegna, Khateb, Murray, Landis, & Michel, 2002; Proverbio & Zani, 2002). In general agreement with this time course of the N1 modulation, results from studies that employed magnetoencephalography (MEG) showed that Kanizsa figures are associated with early activations in the occipital pole \sim 100 ms after stimulus onset, followed by a second peak ~130-150 ms post stimulus onset in the lateral occipital complex (LOC; Abu Bakar, Liu, Conci, Elliott, & Ioannides, 2008; Halgren, Mendola, Chong, & Dale, 2003; Ohtani et al., 2002). In addition, while early activations in the occipital pole have been found to be specific to presentations of a Kanizsa figure in the center of the visual field, the response within the LOC persisted also with peripheral stimulus presentations (Abu Bakar et al., 2008). Thus, convergent evidence suggests that the major response associated with the generation of an illusory figure occurs within 170 ms in the N1 time range. Moreover, findings from neuroimaging studies show that illusory figures differentially activate striate and extrastriate visual areas (e.g., Maertens & Pollmann, 2005; Stanley & Rubin, 2003; see also Seghier & Vuilleumier, 2006, for a review), with potential generators of the N1 being located in lateral occipital regions (Kruggel, Herrmann, Wiggins, & von Cramon, 2001).

However, while the completion of global shapes in Kanizsa figures appears to be associated with relatively early visuo-cortical structures, the concurrent attentional selection of a given Kanizsa square target among nontargets was found to elicit differential activity at later stages of processing: Conci, Gramann, Müller, and Elliott (2006) carried out an electrophysiological study in which observers had to detect a (Kanizsa) target configuration among (two) candidate objects (see Fig. 2B for an example display). Under these circumstances, no differential effect was found for the N1 component; instead, search performance was now systematically mirrored in the pattern of the Posterior Contralateral Negativity (PCN),¹ which, in this instance, occurred within the time range of the N2. Specifically, the amplitude of the PCN was found to reflect the efficiency of Kanizsa figure detection, that is: more negative-going deflections of the PCN (indicating a greater degree of lateralization) were elicited when the nontargets comprised (non-interfering) local groupings rather than (interfering) partial global shapes (which are more similar to the global Kanizsa square target). Thus, in accordance with the general interpretation of this component - namely, as reflecting the allocation of attentional resources to a selected target (position) based on perceptual stimulus characteristics (Eimer, 1996; Luck & Hillyard, 1994) - this pattern of results demonstrates that target selection is significantly affected by the presentation of (non-target) global form information.

In summary, the processing of global shape information in Kanizsa figures appears to be related to an early (N1) component that is modulated by the sensory characteristics of the to-begrouped fragments (e.g., Herrmann et al., 1999), whereas later activity within the N2 time-range reflects processes of attentional

¹ This component is also known as 'N2-posterior-contralateral' or N2pc (Eimer, 1996; Luck & Hillyard, 1994). However, we prefer to refer to it as 'PCN' in the current context to highlight its independence (in terms of latency and amplitude) of the non-lateralized N2 (e.g., Jaskowski, van der Lubbe, Schlotterbeck, & Verleger, 2002; Shedden & Nordgard, 2001).



Fig. 2. (A) Possible pairs of target and nontarget configurations in the global and local search conditions. The global target was defined as a Kanizsa square, induced by four inward-oriented (and edge-aligned) pacman elements; easy and difficult nontargets varied in the extent to which the pacman elements induced a competing global surface. The local target was defined as a 'nonsquare' grouping, made up of four outward-oriented pacman elements; easy and difficult nontargets varied in the extent to which the local pacman orientations matched those of the target. The numbers to the right of each nontarget configuration correspond to the mean slopes of the search RT/set size functions (in ms/item) for each target-nontarget pair as observed by Conci et al. (2007). (B) Example of a target-present search display, illustrating the two possible stimulus locations in the experiment (see Section 2).

selection of a grouped target object over a nontarget configuration (Conci et al., 2006). According to this view, in an initial step of processing, objects are bound to form coherent units that are then available for attentional processing (see also Senkowski, Röttger, Grimm, Foxe, & Herrmann, 2005). However, it is not clear how selection of a target differs when comparing more versus less efficiently bound (target) objects – for instance, when comparing search at global and local hierarchical levels of representation. For example, in Kanizsa figures, search for a globally defined object could potentially benefit from the presence of a well-bound illusory figure (Fig. 1B), whereas search for a local target configuration (Fig. 1C) would require detection of a relatively weaker binding of elements that lack a corresponding illusory figure.

The present study was designed to investigate this hierarchical search asymmetry, namely, how target processing differs in search when the target comprises primarily either global or local object levels. To this end, we employed a visual search paradigm that presented Kanizsa target and nontarget configurations comparable to those used in the previous study of Conci et al. (2006). In a condition of global search, observers were presented with displays that could contain a Kanizsa square target among nontargets (see Fig. 2B for an example display), and nontargets were either non-interfering (i.e., "easy") or interfering (i.e., "difficult"; see Fig. 2A-global for example stimulus configurations). Conversely, in local search, displays could contain a target that was defined as a local stimulus arrangement, and nontargets were designed to yield comparable non-interfering (easy) and interfering (difficult) configurations (see Fig. 2A–local for example stimulus configurations). As elaborated above, both the target-relevant hierarchical level of encoding and the similarity-based nontarget interference have been shown to strongly influence search efficiency (Conci et al., 2007). Here, we examined how global and local searches differ in terms of their electrophysiological activation patterns. Specifically, we investigated the time-course of this hierarchical search asymmetry by analyzing both early visually evoked potentials (P1, N1), as well as components that reflect the allocation of attention (N2, PCN) and subsequent task-related processes within the P3 complex.

2. Methods

Apparatus and stimuli, Stimulus generation, event timing, and trigger signals were controlled by an IBM-PC compatible computer. Stimuli were presented in gray (1.83 cd/m²) against black background (0.02 cd/m²) in the bottom left and right quadrants of a 19-inch computer monitor (1024×768 pixel screen resolution, 85 Hz refresh rate). Each stimulus configuration, composed of four pacman inducers with a diameter of 0.7° , was diagonally offset by 4.1° of visual angle from a centrally presented fixation cross (see Fig. 2B for an example display). At a viewing distance of 80 cm, each candidate grouping subtended a viewing angle of $2.3^{\circ} \times 2.3^{\circ}$. As depicted in Fig. 2A (top), the target was either defined as a global Kanizsa square, or as a local 'nonsquare' grouping (with pacmen inducers rotated outwards by 180°). Both global and local target configurations consisted of a symmetric stimulus representation, with identical physical stimulus characteristics, similar inducer orientations, and equal object complexities (measured in terms of the possible object rotations and reflections; see Garner & Clement, 1963). Thus, the only major difference between the global and local targets was the presence or absence of an illusory square. Nontarget configurations were constructed by rotating inducer elements such that these could be categorized as easy or difficult types: for the easy nontargets, all four pacman inducers were rotated by 180° relative to the inducers of the target (see Fig. 2A. middle). By contrast, difficult nontargets were arranged such that they increased in similarity to the target: two neighboring inducers of a nontarget configuration were randomly selected and rotated by 180°, whereas the other two inducers were identical in orientation to those of the target (see Fig. 2A, bottom). This partial overlap of inducer orientations increased the target-nontarget similarity either in terms of the global (illusory) surface or with regard to the local inducer arrangement. Note, that feature contrast between target and nontargets was identical for both global and local search, with equal changes in inducer orientation for a target relative to a given nontarget configuration.

Procedure. Participants were seated in a dimly lit, soundproof experimental chamber. Each trial started with the presentation of a fixation cross for a randomized period of 500–600 ms at the screen center. Subsequently, the two candidate target configurations were presented in the bottom left and right quadrants of the display. Following stimulus onset, observers were to maintain central fixation and make a speeded target-absent versus target-present RT response via mouse keys. Displays remained on screen for 200 ms, after which a blank screen with central fixation cross was presented until a response was given. In case of an erroneous response or a time-out (after 2500 ms), feedback was provided by a computer-generated tone and an alerting message ('Error' or 'Time-out') that was presented for 1000 ms at the center of the screen. Each trial was followed by an inter-stimulus-interval of 1000 ms.

The experiment was divided into two consecutive sessions, each dedicated to either global or local search. Each session started with 50–100 practice trials to familiarize participants with the task and in order to achieve a performance level with a maximum of ~10% of response errors. Subsequently, for each session, 720 experimental trials were presented in six blocks of 120 trials each. The order of sessions (global or local search) and the response mapping (i.e., left- or right-hand responses to target presence) was counterbalanced across both halves of the experiment and observers, to control for practice and compatibility effects between stimulus position and response hand (Fitts & Seeger, 1953). Within each session, the nontarget type was kept constant throughout a block of trials, with all blocks presented in pseudorandom order on an observer-by-observer basis. Search displays contained a target on 2/3 of all trials (and no target on 1/3 of all trials), with targets presented equally likely in the left and right (lower) quadrants of the search display.

Participants. Twelve right-handed volunteers (10 men; mean age: 25.2 years) with normal or corrected-to-normal visual acuity participated in the experiment for payment of €8.00 per hour. All observers provided written informed consent, and the experimental procedure was approved by the ethics committee of the Department of Psychology, Ludwig-Maximilians-University, Munich.

In summary, the independent variables were target (present-left, present-right, absent), search level (global, local), and nontarget type (easy, difficult), with 120 trials per condition.

EEG recording. The electroencephalogram (EEG) was recorded continuously, at a sampling rate of 1000 Hz, using 64 Ag/AgCl electrodes including those corresponding to the extended 10–10 system. The electrodes were mounted on an elastic cap (Easy Cap, Falk Minow Services). Horizontal and vertical eye movements were monitored by means of electrodes placed at the outer canthi of the eyes and the superior and inferior orbits. Electrophysiological signals were amplified using a 0.1–100-Hz bandpass filter via BrainAmps (Brain Products, Munich). All electrodes were referenced to Cz and re-referenced off-line to linked mastoids. ERPs were averaged off-line over an 800-ms epoch relative to a 200-ms prestimulus baseline. Eye movements were corrected by means of independent component analyses (ICA) as implemented in the Brain Vision Analyzer software (Brain Products, Munich). Epochs with artifacts, that is, excessive peak-to-peak deflections (>60 μ V or <-60 μ V), bursts of electromyographic activity (permitted maximal voltage step/sampling points 50 μ V), and activity lower than 0.5 μ V within intervals of 500 ms, were excluded from averaging on an individual-channel basis.

Data analysis. The experiment was designed to determine electrophysiological components that are sensitive to target–nontarget interference at global and local hierarchical levels of representation. Consequently, only target–present trials were included in the analysis of behavioral performance and ERPs.

First, for the analysis of the *behavioral performance*, trials on which a response error was made (6.6%; target misses: 4.5%) were removed from the data set prior to the RT analysis. RTs and error rates were each analyzed by means of a repeated-measures analysis of variance (ANOVA) with the factors search level (global, local) and nontarget type (easy, difficult).

Second, analyses of the *ERP effects* were carried out following the elimination of artifacts and trials with an incorrect response. Latency windows of the P1, N1, N2, P3, and slow wave (SW) components were determined individually as the maximum deflection within the following post-stimulus time windows (derived by visual inspection of the grand average potentials): P1: 75–125 ms; N1: 140–190 ms; N2: 240–300 ms; P3: 300–380 ms; SW: 380–500 ms.

Statistical analyses of the *P1*, *N1*, and *N2* components were performed on the mean amplitudes within the pre-selected latency windows at posterior occipital (O1, O2), parieto-occipital (PO7, PO8), and parietal (P7, P8) electrodes. For statistically comparing the mean amplitudes, repeated-measures ANOVAs were performed with the factors search level (global, local), nontarget type (easy, difficult), target position (contralateral, ipsilateral to electrode), and electrode site (occipital, parieto-occipital and parietal electrodes).

Next, for the statistical examination of the *P3 and SW components*, analyses were performed on the mean amplitudes within the pre-selected latency windows at occipital (O1/Oz/O2), parieto-occipital (PO7/POz/PO8), and parietal (P7/Pz/P8) posterior electrodes. Repeated-measures ANOVAs were performed with the factors search level (global, local), nontarget type (easy, difficult), electrode position (electrodes over the left, the midline, and the right hemisphere), and electrode site (occipital, parieto-occipital and parietal electrodes). Note that for all non-lateralized analyses (P1, N1, N2, P3, and SW), statistically significant results were considered only if the experimental factors search level and nontarget type were included in the effects.

Finally, the PCN was computed by subtracting ERPs obtained at lateral posterior electrodes PO7/PO8 ipsilateral to the target location from contralateral ERPs. Statistical analyses were conducted for PCN peak latencies (determined individually as the maximum negative deflection in the 240–450 ms time window post-stimulus) and mean amplitudes (averaging five sample points before and after the maximum deflection). Repeated-measures ANOVAs were performed on the mean amplitudes and peak latencies with the factors search level (global, local) and nontarget type (easy, difficult). Subsequent mixed-design ANOVAs were also performed on amplitudes and latencies with session order (global–local, local–global) as between-subject factor and search level and nontarget type as within-subject factors.

3. Results

Behavioral performance: RTs. Fig. 3 presents the mean correct target-present RTs (A) and associated error percentages (B) as a function of the (global and local) search level, separately for easy and difficult nontarget types. The repeated-measures ANOVA performed on the RTs revealed significant main effects for search level [F(1,11) = 16.57, p < .003] and nontarget type [F(1,11) = 8.83, p < .02]: search was 89 ms slower for local as compared to global search conditions, and 21 ms slower with displays containing a difficult as compared to an easy nontarget type. In addition, the search level x nontarget type interaction was significant [F(1,11) = 11.66, p < .007], due to a 39-ms increase in RTs from the easy to the difficult nontarget type in local search (p < .008), but no reliable increase for global search (7 ms, p = .19).



Fig. 3. (A) Mean target-present reaction times (RTs) and (B) associated error percentages (with corresponding standard error bars) as a function of the global or, respectively, local target configuration. The solid [dashed] lines and the black [white] bars correspond to the response latencies and errors for easy [difficult] nontargets, respectively.

Errors. Next, the repeated-measures ANOVA on the error rates revealed, as above, significant main effects for search level [F(1,11) = 16.82, p < .003] and nontarget type [F(1,11) = 18.48, p < .002], as well as a significant search level × nontarget type interaction [F(1,11) = 4.84, p < .05]. Errors were increased by 2.8% for local as compared to global search, and by 2.1% for difficult as compared to easy nontargets. The interaction term was due to the increase in errors between easy and difficult nontargets being higher for local (3.4%, p < .005) than for global (0.8%, p < .05) search conditions, mirroring the outcome of the RT analysis.

ERP effects. Fig. 4 presents grand-average ERPs elicited at occipital, parieto-occipital, and parietal posterior electrodes (bottom, middle and top panels, respectively) in the global and local search conditions, separately for easy and difficult nontarget types.

P1. Statistical analysis of the P1 component revealed a significant main effect of search level [F(1,11) = 7.16, p < .03], showing more positive-going deflections in global as compared to local search (1.8 μ V vs. 1.4 μ V).

N1. Next, within the N1 latency window, the repeated-measures ANOVA revealed a (borderline) significant interaction of search level and target position [F(1,11)=4.72, p=.05]. This interaction shows that the N1 elicited a greater negativity contralateral to a target in global search, but the reverse, namely a greater negativity ipsilateral to targets, in local search (mean amplitude differences between contralateral and ipsilateral target presentations: $0.2 \,\mu V$ [$-0.1 \,\mu V$] for global [local] search; see Figs. 5 and 6 for the global and local search conditions, respectively: differences between contralateral and ipsilateral target presentations are particularly prominent with easy nontargets). Thus, the N1 amplitude basically correlates with the presence of the illusory figure in that it shows a more pronounced response to the global shape representation irrespective of whether it was the target (in global search) or the nontarget (in local search).

N2. The analysis of the N2 component again revealed a main effect of search level [F(1,11)=5.52, p < .04], with more positive amplitudes in global as compared to local search (2.7 μ V and 1.8 μ V; see Fig. 4). Moreover, there was a significant interaction of



Fig. 4. Grand-average ERP waveforms elicited over occipital (O1/O2/O2), parieto-occipital (PO7/PO8), and parietal (P7/Pz/P8) posterior electrodes for easy (solid) and difficult (dashed) nontarget types in global (black) and local (gray) search conditions. Graphs are plotted with negative voltages upward and time zero representing stimulus onset.

search level with target position [F(1,11) = 22.04, p < .002], owing to a larger degree of lateralization in global than in local search (mean amplitude differences between contralateral and ipsilateral target presentations: $1.1 \,\mu\text{V}$ [$-0.1 \,\mu\text{V}$] for global [local] search; compare Figs. 5 and 6 for the global versus local search conditions). Note that differences between contra- and ipsilateral target presentations are also reflected in the PCN (see PCN analysis presented below).

*P*3. Statistical analysis of the P3 component showed a significant main effect of search level [F(1,11) = 27.51, p < .001], as well as a significant interaction of search level × electrode site [F(2,22) = 11.29, p < .001]. The P3 deflection was more positive-going for global (5.4 µV) than for local search (3.2 µV), with the largest difference between search levels evident at central electrodes (1.9, 2.6 and 2.2 µV for left-, central-, and right-hemisphere electrode sites, respectively; see Fig. 4).

SW. The analysis of the SW component revealed significant main effects of search level [F(1,11) = 19.03, p < .002] and nontarget type [F(1,11) = 13.64, p < .005], along with a number of significant interaction effects [nontarget type × electrode position: F(1.6,18.4) = 5.63, p < .02; nontarget type × electrode position × electrode site: F(1.6,18.3) = 12.36, p < .001; search level × electrode position × electrode site: F(1.9,21.7) = 5.35,

p < .02]. Positive amplitude deflections were (by 1.7μ V) larger in global compared to local search, and (by 0.7μ V) larger for easy compared to difficult nontargets. Moreover, the significant interactions were due to the search level effect being centered at electrode Pz, whereas the influence of nontarget type was primarily evident at central, parietal, and parieto-occipital electrodes (see Fig. 4, electrodes Pz and POz).

PCN. Figs. 5 and 6 present the lateralized, grand-average waveforms elicited at occipital, parieto-occipital, and parietal posterior electrodes (bottom, middle, and top panels, respectively). ERPs are shown contralateral and ipsilateral to a target, together with the resulting difference waves (contralateral minus ipsilateral), for the global and local search conditions (Figs. 5 and 6, respectively), separately for easy and difficult nontarget types. As can be seen, in global search, the PCN was evident within the N2 time range between ~250 and 350 ms after stimulus onset (Fig. 5, right column). In contrast, in local search, the PCN occurred only much later, in the time range between ~350 and 450 ms (Fig. 6, right column). This marked shift in the elicitation of the PCN was confirmed by statistical analysis, which revealed a significant main effect of search level [F(1,11) = 60.91, p < .001]: the PCN peaked significantly earlier in global than in local search (294 ms vs. 364 ms). In contrast, there



Fig. 5. Lateralized grand-average ERP waveforms in the global search condition, elicited at occipital (O1/O2), parieto-occipital (PO7/PO8), and parietal (P7/P8) posterior electrodes contralateral (solid) and ipsilateral to a target (dashed). Waveforms are plotted for easy (left column; black) and difficult (central column; gray) nontarget types, together with the difference between contra- and ipsilateral ERPs (dotted lines; right column). Graphs are plotted with negative voltages upward and time zero representing stimulus onsets.

was no significant difference in latency between easy versus and difficult nontarget types (327 ms vs. 331 ms; all p's > .26).

A further, mixed-design ANOVA revealed the *PCN latencies* to be also dependent on the order in which global and local search sessions were administered, that is, the main (between-subjects) effect of session order was significant [F(1,10)=27.05, p < .001] (besides the main effect of search level, which was already described above): the PCN peaked 33 ms earlier for whatever condition (global or local) was performed second. This effect of order is particularly prominent in Fig. 6 (right column, electrodes PO7/PO8), where the waveform of the PCN appears to consist of two sequential components (with the sequential peaks corresponding to the

order differences). However, there were no significant interactions involving the factor session order (all *p*'s > .35), indicating that prolonged practice shortens the PCN latencies, for all types of stimulus material.

The ANOVA of the *PCN amplitudes* revealed a significant main effect of nontarget type [F(1,11) = 9.18, p < .02]: amplitudes were more negative-going for easy as compared to difficult nontarget types ($-2.9 \,\mu$ V vs. $-1.9 \,\mu$ V, respectively). In addition, a significant search level by nontarget type interaction [F(1,11) = 10.32, p < .01] revealed the amplitude difference between easy and difficult nontargets to be more marked for local than for global targets (differences of $-1.4 \,\mu$ V and $-0.5 \,\mu$ V, respectively; see Figs. 6 and 5,



Fig. 6. Lateralized grand-average ERP waveforms in the local search condition, elicited at occipital (01/02), parieto-occipital (PO7/PO8), and parietal (P7/P8) posterior electrodes contralateral (solid) and ipsilateral to a target (dashed). Waveforms are plotted for easy (left column; black) and difficult (central column; gray) nontarget types, together with the difference between contra- and ipsilateral ERPs (dotted lines; right column). Graphs are plotted with negative voltages upward and time zero representing stimulus onsets.

respectively), mirroring the behavioral pattern of (RT and error) effects.

To examine for possible influences of session order on the PCN amplitudes, a mixed-design ANOVA was performed identical to that of the PCN latencies. This analysis revealed no significant effects involving the (in this context interesting) between-subjects factor session order (all p's > .35).

4. Discussion

The current study was performed to isolate the electrophysiological time-course of processing hierarchical, global and, respectively, local object levels in visual search for Kanizsa figures. The behavioral results replicated previous findings of a search asymmetry (Conci et al., 2007; see Fig. 3): both RTs and error rates indicated that global search was more efficient than local search. Furthermore, difficult nontarget configurations interfered more with target detection than easy configurations, and this effect was particularly pronounced for local, as compared to global, search. This pattern replicates the finding that global search for an illusory square has precedence over search for a local grouping and that similarity-based nontarget interference occurs at the particular hierarchical level at which the information critical for target detection is represented.

In the electrophysiological data, the costs for local as compared to global searches were systematically reflected in amplitude (and latency) variations in a number of ERP components: a reliable increase in amplitude for global (relative to local) search was already observable for the early, visually evoked potentials, in particular the P1 (75–125 ms; see Fig. 4), followed by a slight preference in processing global objects as indexed by an N1 amplitude modulation (140-190 ms; see Figs. 5 and 6). Next, the N2 (240-300 ms) component again revealed a difference between global and local search, along with an increased negativity for difficult (as compared to easy) nontarget types. Moreover, a difference in attentional orienting towards the target was also reflected in the timing of the PCN component, with a substantial delay (of \sim 70 ms) in search for local, as compared to global, targets (see Figs. 5 and 6). In addition, nontarget interference was found to primarily influence the amplitude of the PCN: easy nontarget types were associated with more negative-going amplitudes than difficult nontargets (and this difference in amplitudes was stronger in local, as compared to global search, mirroring the pattern of behavioral effects described above). This corresponds to a larger degree of lateralization in search with less interfering (easy) nontargets, indicating that orienting towards the target was more pronounced with easy, as compared to difficult, nontargets. Finally, task-related processing in the P3 (300-380 ms) showed a stronger positive-going deflection for global (as compared to local) search, followed by a modulation of the SW (380-500 ms) component that scaled according to the overall search efficiency (reflecting both the hierarchical object level and similarity-based target-nontarget processing; see Fig. 4). Thus, in summary, all sensory (P1, N1), attentional (N2, PCN), and task-related (P3, SW) components revealed that global search elicited stronger (and faster) neurophysiological responses than local search, with similarity-based target-nontarget encoding occurring only from the time range of the N2 onwards.

In general agreement with previous EEG studies, the current experiment shows that early visually evoked potentials are responsive to global shape in Kanizsa figures. Our results demonstrate an effect of global precedence already in the P1 and N1 components. While a number of studies have reported an effect on the N1 component (Brodeur et al., 2006; Herrmann & Bosch, 2001; Proverbio & Zani, 2002; Martinez et al., 2007; Murray et al., 2004, 2002; Pegna et al., 2002; Proverbio & Zani, 2002), a P1 modulation

has so far only been found in a study that presented the illusory figure independently of the onset of the figure inducers (Brodeur, Lepore, Lepage, Bacon, & Debruille, 2008). Thus, convergent evidence from a number of electrophysiological studies suggests that visually evoked components are capable of signaling the illusory (global) object of an integrated Kanizsa figure as early as 70 ms after stimulus onset (see also Abu Bakar et al., 2008, for comparable early effects in an MEG-experiment). Furthermore, the early hierarchical modulation of the P1 and N1 components suggests that integrated global object information is already available at the initial, preattentive stages of processing in visual search (e.g., Conci, Böbel, et al., 2009).

Interestingly, the N1 component not only reflected a general difference between global and local search, but also showed an amplitude modulation linked to the stimulus configuration that contained global object information, whatever the task. Thus, in global search, the N1 was found to be larger contralateral to the target (containing global, object information); in local search, by contrast, this pattern reversed, with a larger N1 occurring contralateral to the nontarget (that contained global shape information; see Figs. 5 and 6). This pattern might be interpreted in terms of an early sensitivity to the global pattern of a coherent object (i.e., the illusory Kanizsa square) with N1 modulations occurring independently of the top-down task set (see Herrmann & Bosch, 2001). Thus, initially, a well-bound global shape is processed with priority. However, it should be noted that this preference for the illusory square was relatively weak and confined solely to the timewindow of the N1 component. Other than that, the task-set (global or local search) largely determined which aspect of the stimulus was processed with priority (see also Fig. 6, which does not reveal evidence for a positive deflection towards the task-irrelevant nontarget in local search). Thus, this outcome shows that search is performed primarily on the basis of the pre-defined target description, with differences in performance varying according to the ease with which an object can be bound to form a coherent unit (for global or local stimulus configurations).

Subsequent to these effects observed in early, sensory components, the PCN (and N2) component deflections showed close correspondences to other studies concerned with the allocation of attention in complex (composite) objects. For instance, in the current study, the PCN was found to be dependent on the degree to which the target could be disambiguated from a set of nontargets - which corresponds to findings of Conci et al. (2006) showing that the amplitude of the PCN reflects search efficiency in a task requiring detection of a Kanizsa square. Similarly, the present results indicate that both global and local search give rise to amplitude modulations dependent on the degree to which interfering information is presented concurrently with a given target. When target and nontarget attributes overlap, interference is increased - reducing the PCN amplitude and, correspondingly, the strength with which the target summons focal attention. In search for a global target, global shape information in nontargets interferes and modulates the PCN amplitude; conversely, but similarly, in search for local targets, local inducer orientation in nontargets determines the degree to which search interference, and PCN amplitude modulations, arises. While the pattern of nontarget interference was comparable for global and local search, the modulation of the PCN amplitude was found to be stronger in search for a local target configuration. This suggests that nontarget interference in the PCN scales not only relative to the target-nontarget overlap, but also reflects to some extent the overall efficiency of search. However, importantly, the resolution of nontarget interference during search appears to operate later (from the time-range of the N2 onwards) than the extraction of shape information (according to a pre-defined target description), as is evident from the initial processing stages.

Thus, in summary, the variations of the PCN amplitude are likely to be indicative of a relatively general-purpose mechanism reflecting search efficiency for complex groupings (such as Kanizsa figures) as well as more simple stimulus configurations. For instance, Luck and Hillyard (1994) demonstrated that a PCN is elicited by 'pop-out' targets defined within a given (fixed) feature dimension. In addition, systematic variations of feature overlap between targets and nontargets clearly generate a modulation of the PCN: amplitudes increase with increasing overlap (Hopf, Boelmans, Schoenfeld, Heinze, & Luck, 2002). In this regard, the degree of similarity between the target and the nontargets not only relates to search efficiency (at a behavioral level), but also to the overlap of electrophysiological responses (Sripati & Olson, 2010). In light of these findings, and consistent with the current pattern of results, the PCN has been suggested to reflect a process of 'ambiguity resolution' (Luck, Girelli, McDermott, & Ford, 1997), mirroring the ease with which a given target is segregated from a set of nontargets in terms of basic features (e.g., color, orientation) and more complex feature conjunctions.

In addition to nontarget effects on the detectability of the target, hierarchical object representations also had a profound influence on search performance (and the PCN). Search was relatively efficient for global configurations, with PCN latency roughly corresponding to that found with search for simple feature targets (see, e.g., Töllner, Gramann, Müller, Kiss, & Eimer, 2008; Töllner, Zehetleitner, Gramann, & Müller, 2010). By contrast, when the target was defined as a local configuration, search was slowed and the PCN peak latency shifted from 294 to 364 ms. On previous evidence, the PCN latency provides a marker of how efficiently focal attention is allocated to the target (e.g., Luck et al., 2006; Töllner, Zehetleitner, Gramann, & Müller, 2011; Töllner, Zehetleitner, Krummenacher, & Müller, 2011). Accordingly, the differential PCN timing between global and local searches would be indicative of stimulus encoding being prolonged (by \sim 70 ms) when the target is defined as a local, rather than a global, configuration, thus delaying the allocation of focal attention to the target.

A possible explanation for the PCN latency difference between global and local search is that information specified at different hierarchical levels requires differential depths of processing. For instance, in global search, detection of a Kanizsa square is based on the extraction of a global shape that can be bound efficiently (i.e., rapidly). By contrast, in local search, successful target detection requires more elaborate (i.e., time-consuming) processes of local-element grouping. On this view, global precedence would arise because the outputs of sensory processes coding the global configuration become available earlier than those involving the integration of local assemblies. Accordingly, the shift in PCN latency observed in local relative to global search could be explained with reference to the more pronounced input provided by the earlier modulations of the P1 (and N1) component(s) with global Kanizsa shape information, that is: increased amplitudes of early visual components for global objects might subsequently translate into efficient (i.e., fast) allocation of attentional resources, as reflected in the PCN. Moreover, the global precedence effect manifest in the N1 (i.e., the increase in amplitude for the irrelevant, but global nontarget in local search) could be another, complementary source for the slowed attentional orienting towards the target in local search. Accordingly, orienting towards the target in local search, as indexed by the PCN, might be slowed because processing of the stimulus configuration (in the N1) prioritizes to some extent the global (yet task-irrelevant) nontarget. Taken together, the efficiency with which an object can be bound into a coherent unit at an initial processing stage for a given task determines the ease with which it can subsequently be selected by focal attention (see also McMains & Kastner, 2010; Senkowski et al., 2005).

In addition to the early, visually evoked components, later potentials also exhibited a time course revealing an initial differentiation between hierarchical processing stages (in the P3), followed by SW amplitude modulations that reflected the overall efficiency of search. Specifically, the P3 scaled only according to the differential efficiency between global and local search. This was followed by a differentiation in the SW component, which showed combined sensitivity to the hierarchical object level (global vs. local) and the degree of search interference (easy vs. difficult nontargets). Thus, the SW exhibited larger positive deflections with more efficient search, where efficiency depended on both the search level and on nontarget interference (see Fig. 4). Typically, the P3 has been associated with the processing of task-relevant target stimuli, in particular with regard to stimulus categorization and identification (see Kok, 2001, for a review) or memory updating (Donchin & Coles, 1988). On this view, the P3 reflects a mechanism involved in comparing a given stimulus to a stored memory representation (e.g., a target template), with the P3 and SW waveforms being indicative of the efficiency with which this comparison is made. For example, García-Larrea and Cézanne-Bert (1998) reported that an increase in task difficulty was associated with a decrease in P3 and SW amplitudes. Accordingly, in the current study, a more demanding search task was associated with reduced P3 and SW amplitudes. Taken together with the earlier pattern of effects (discussed above), this suggests that the complexity of a stimulus in a search task determines processing throughout a series of consecutive processes and is even reflected in relatively late, more response-related components

In summary, our results show that processing of a hierarchical stimulus in visual search can be related to multiple components across the entire chain of information processing: early sensory analysis, the subsequent (attentional) selection of the target, and task-related processes all mirrored the difference between global and local target search. Moreover, whereas early sensory processes (P1, N1) primarily reflected preferential processing of global (over local) stimulus attributes, the subsequent attentional selection (as reflected in the PCN) was found to also depend on (resolving) similarities between the target and nontarget stimuli. Finally, the P3 complex (in particular, the SW component) were influenced by the overall task difficulty, suggesting that the process of completing and selecting an object is determined by a complex cascade of processes that reflect mechanisms of object segmentation at multiple levels of the neuronal processing hierarchy.

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