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The computation of shape orientation in search for Kanizsa figures

Markus Conci, Hermann J Müller, Mark A Elliott¶
Allgemeine und Experimentelle Psychologie, Department Psychologie, Ludwig-Maximilians Universität, Leopoldstrasse 13, D 80802 Munich, Germany; e-mail: conci@psy.uni-muenchen.de; ¶ Department of Psychology, National University of Ireland, Galway, Ireland
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Abstract. Previous studies of visual search for illusory figures have provided equivocal results, with efficient search for Kanizsa squares (eg Davis and Driver, 1994 *Nature* **371** 291 – 293) contrasting with inefficient search for Kanizsa triangles (eg Grabowecky and Treisman, 1989 *Investigative Ophthalmology and Visual Science* **30** 457). Here, we investigated whether shape orientation can explain these differences. The results from three experiments replicated previous findings: Kanizsa squares in experiment 1 could be detected more efficiently than Kanizsa triangles in experiment 2. In addition, when controlling for stimulus complexity in experiment 3, we found search for Kanizsa diamonds intermediate in efficiency. Taken together, these results suggest an oblique effect in search for Kanizsa figures with cardinal shape orientations leading to more efficient performance than oblique shape orientations. Our findings indicate that both shape orientation and stimulus complexity affect search for illusory figures.

1 Introduction

Natural scenes typically consist of multiple, fragmentary, and overlapping forms which the visual system integrates without apparent effort into coherent wholes ('objects'). Structuring complex input from the ambient visual array is, in general, achieved by means of grouping operations (eg Wertheimer 1923; Koffka 1935). In agreement with a cardinal role for grouping in generating perceptual structure, the processing of configural information has been shown to provide one basis (besides simple feature-based coding) for subsequent attentional selection (Pomerantz et al 1977; Rensink and Enns 1995). Similarly, basic Gestalt principles such as item similarity (Duncan and Humphreys 1989), closure (Donnelly et al 1991; Conci et al 2007a), and, in more general terms, figural goodness—as assessed by stimulus complexity measures (Rauschenberger and Yantis 2006)—have been shown to influence stimulus processing at early, preattentive stages of processing.

A particularly strong case in support of the idea that attentional selection is based on prior grouping is provided by the perception of illusory figures. An example of an illusory Kanizsa figure (Kanizsa 1955) is shown in figure 1a, T. As can be seen, the collinear arrangement of 'pacman'-like inducers leads to the completion of an illusory object that lacks a direct physical correlate. This shape consists of sharp contour boundaries and a surface that appears to be brighter than the background. The latter feature illustrates a qualitative difference that goes beyond the properties of a simple grouping of the physically specified inducers. The emergence of this complex percept has been attributed to the parallel operation of two separable subsystems, one responsible for computing the (illusory) contour boundaries and the other for filling-in corresponding surface portions (Grossberg and Mingolla 1985), with both systems relying on segregated anatomical structures in the ventral visual stream (see Seghier and Vuilleumier 2006, for review).

The preattentive character of the parallel and distributed processing of illusory figures is demonstrated by visual-search performance: search for Kanizsa figures has been shown to be efficient (Davis and Driver 1994; see also Gurnsey et al 1992).

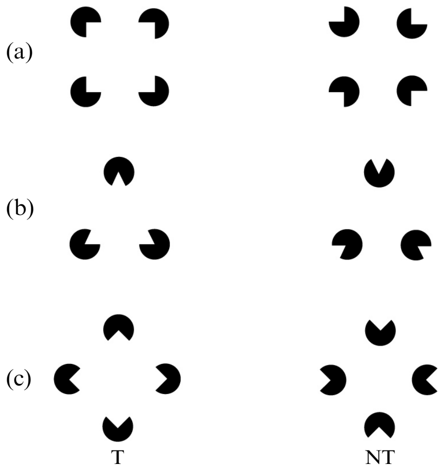


Figure 1. Examples of square (a), triangle (b), and diamond (c) stimulus configurations, either forming the target (T) Kanizsa figures (left column) or corresponding non-target (NT) groupings (right column).

In the study of Davis and Driver, observers were asked to search for a Kanizsa target square (figure 1a, T) among comparable non-target configurations (that were presented with the same pacman inducers, but rearranged such that no illusory figure could be perceived; see figure 1a, NT). The results showed that search could be performed in parallel, that is the reaction times (RTs) to detect the target were independent of the number of configurations presented in the search display (the display size).

According to Davis and Driver (1994), parallel search for Kanizsa figures is attributable to (preattentive) mechanisms that encode illusory contours in area V2 (von der Heydt et al 1984). However, this is at odds with Gurnsey et al (1996), who re-examined whether Kanizsa-type illusory contours are the basis for efficient search. While adhering to the general method of Davis and Driver, Gurnsey et al (1996) found search performance to be independent of the contour specifications—arguing that efficient search for Kanizsa figures is not critically dependent on the presence of illusory contours. Follow-up studies were designed to investigate more specifically which attributes of an illusory figure mediate efficient detection (Conci et al 2006, 2007b). These studies provided evidence that attention is not, in fact, guided by the illusory contours, but instead by surface information given by the whole figure. In general agreement with these findings, a recent study by X Li et al (2008) compared search for different types of contour and found evidence to suggest that attention is not guided by the presence of illusory contours [whereas, for offset gratings, the illusory contours were found to be encoded in parallel; see also Gurnsey et al (1992) for a comparable finding]. Thus, converging evidence from a series of studies that employed Kanizsa-type stimuli suggests that it is not the exact specification of the illusory contours that guides search, but rather processes of surface filling-in that have been implicated in extracting a crude 'salient region' (Stanley and Rubin 2005).(1)

In addition to the debate about which specific figural characteristics promote Kanizsa figure detection, conflicting evidence as to the locus of illusory-figure completion (preattentive versus attentional) was presented by Grabowecky and Treisman (1989).

(1) Efficient guidance in search for Kanizsa figures is interpreted as being based on crude region information derived from surface filling-in processes (Conci et al 2006, 2007b; Stanley and Rubin 2005). However, when search for illusory figures is compared with search for real figures, performance is clearly poorer for a target defined by an illusory, rather than a similar real, surface (X Li et al 2008). Nevertheless, search for an illusory figure is far more efficient than search for a comparable configuration that lacks an illusory surface (Conci et al 2007b). Thus, search performance appears to be graded, with processing efficiency increasing to the extent that 'redundant' information supports target detection (ie no surface $<$ illusory surface $<$ real surface).

They reported search for Kanizsa triangles to be inefficient and dependent on display size—unlike search for Kanizsa squares which was relatively efficient and independent of display size. Thus, a comparison of this study with that of Davis and Driver suggests that not all illusory figures are created equally (cf Grabowecky et al 1997) and that different stimulus shapes may influence search performance differently. One possibility is that the orientation of the illusory shape influences the efficiency of completion. As already shown, horizontal and vertical shape orientations are integrated more efficiently than oblique orientations for both real (Appelle 1972) and illusory (Purghe 1989; Ehrenstein and Hamada 1995) objects. However, it is not clear whether search is performed on the basis of these integrations and whether the extraction of a crude salient region (Conci et al 2007a, 2007b) is sensitive to such relatively fine-grade orientation differences.

An 'oblique effect' might offer one explanation for the observed differences in search performance. However, other factors could also have caused the reported differences. For instance, the spatial arrangement of the stimulus configurations in the search displays differed slightly between the studies of Davis and Driver (1994) and Grabowecky and Treisman (1989), and the relative size of the configurations alongside the arrangement of inducers in non-target items could have equally contributed to differences in search—though Grabowecky et al (1997) found non-target arrangement and display organisation not to be crucial. Most importantly, however, the complexity of the stimulus configurations differs between square and triangle configurations. For example, measured in terms of the number of the possible rotations and reflections of a stimulus configuration (the so-called 'R&R-operations'; Garner and Clement 1963), complexity is higher for triangles (R&R = 4) than for squares (R&R = 1). Given that complexity has been shown to critically influence search efficiency (Rauschenberger and Yantis 2006), a similar influence could produce variations in search performance for Kanizsa figures and explain why triangles are harder to detect than squares.

The present study was designed to replicate previous findings in search for Kanizsa figures and examine the potential causes for differences in search efficiency. The discrepant results discussed previously may reflect a critical influence of (illusory) configuration shape on search performance (Grabowecky and Treisman 1989; Davis and Driver 1994; Grabowecky et al 1997). To investigate this, we compared different shape configurations so as to test whether their orientations can explain the reported performance differences.

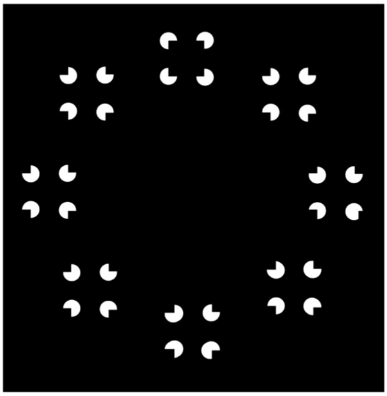
2 Experiment 1

Experiment 1 was performed to determine search efficiency for Kanizsa square targets with displays comparable to those employed in similar search experiments (Davis and Driver 1994; Gurnsey et al 1996; Conci et al 2007b). Search arrays were presented at various display sizes and could contain a Kanizsa square target (T) among square non-target (NT) configurations. Non-targets differed from the target in that pacman-inducers were rotated such that no illusory figure was induced (for examples, see figure 1a).

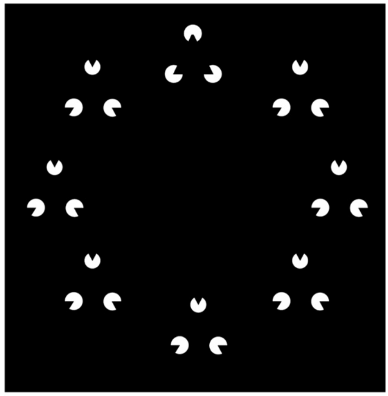
2.1 *Method*

2.1.1 *Participants.* Eight paid observers (two male; mean age = 27.1 years) with normal or corrected-to-normal visual acuity participated in the experiment.

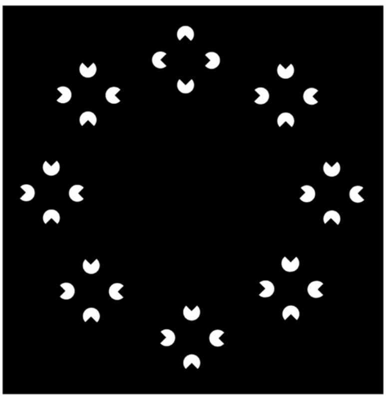
2.1.2 *Stimuli.* Stimuli, created in the C programming-language and generated by an IBM-PC compatible computer running MS-DOS, were presented in light grey (1.83 cd m^{-2}) against a dark (0.02 cd m^{-2}) background at eight possible locations on a 17-inch wide monitor screen. The stimulus configurations were placed on a virtual circle around the screen centre, with radius 8.75 deg of visual angle at a viewing distance



(a)



(b)



(c)

Figure 2. Examples of target-present displays that contain eight candidate groupings showing all possible stimulus locations. Search displays consisted of square (a), triangle (b), or diamond (c) configurations (experiments 1, 2, and 3, respectively).

of 55 cm. An example display with eight stimulus configurations is shown in figure 2a. Each configuration, or 'candidate grouping', was composed of four inducing elements with a diameter of 1 deg arranged in a square-like form that subtended a viewing angle of 2.9 deg $\times$ 2.9 deg. As depicted in figure 1a, the target (T) was defined as a Kanizsa square. In contrast, non-target configurations (NT) were produced by rotating inducer elements by 180° such that the aperture of each inducing element faced away from the centre of each configuration. Trial displays could contain 1, 4, or 8 candidate groupings (the display size). In 50% of the trials, a target was present in the display. For displays with fewer than eight candidate groupings, the stimulus positions were chosen pseudo-randomly from among the eight possible locations—with the constraint that, for display sizes of 4, groupings were presented at every second position of the eight possible locations.

2.1.3 *Procedure.* Each trial started with the presentation of a central fixation cross for 500 ms. The fixation cross was then immediately replaced by the search display, to which observers responded with a speeded target-absent/target-present response via mouse keys. Displays remained on screen until a response was recorded. In the case of an erroneous response or 'time-out' (after 2500 ms without reaction), feedback was given by a computer-generated tone, and an alerting message ('Error' or 'Time-Out') was presented for 500 ms at the screen centre. Each trial was separated from the next by an interval of 500 ms.

The experiment consisted of 40 practice trials followed by 8 experimental blocks of 60 trials. Blocks were administered in pseudo-random order on an observer-by-observer basis. In summary, the independent variables were target (T: present, absent) and display size (DS: 1, 4, 8 configurations), with 40 trials per condition.

2.2 *Results*

For this and all subsequent experiments, trials with RTs 2.5 standard deviations (SDs) above the mean were excluded from the data proper. Fewer than 1% of all trials were eliminated by this outlier criterion (this was the case in all subsequent experiments as well)—see figure 3a for the mean correct RTs, and the associated error rates, presented as a function of display size. Overall, erroneous responses were quite rare (2.5% of all trials; 2.9% misses, 2.2% false alarms). The error rates were examined by means of a repeated-measures analysis of variance (ANOVA) with the factors target and display size. This ANOVA revealed a significant interaction ($T \times DS$: $F_{2,14} = 4.39$, $p < 0.04$),

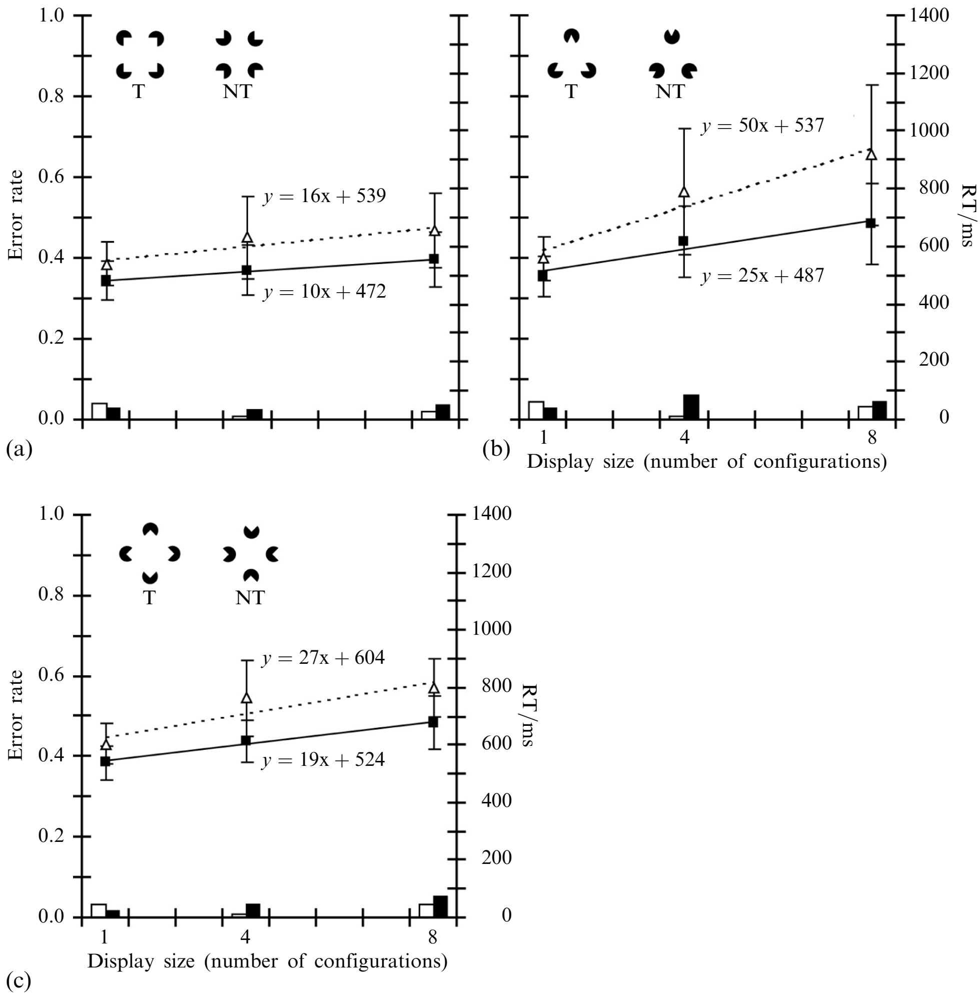


Figure 3. Mean RTs (with bars depicting the SDs) and associated error rates in experiment 1 (a), experiment 2 (b), and experiment 3 (c) as a function of display size. Each graph shows prototype square/triangle/diamond targets and corresponding non-target configurations, with RTs and error rates plotted separately for target absent (dotted line, white bars) and target present (solid line, black bars) trials. In addition, the slope for the best-fitting straight line is given for each RT distribution. T = target, NT = non-target.

with target misses becoming more frequent with increasing display size compared to false alarms.

Next, the mean correct RT data were examined by means of a T × DS repeated-measures ANOVA. This revealed both main effects to be significant (T: $F_{1,7} = 26.85$, $p < 0.001$; DS: $F_{2,14} = 19.84$, $p < 0.001$). Target-absent RTs were slower than target-present RTs, and RTs increased with display size. In addition, the interaction was marginally significant (T × DS: $F_{2,14} = 3.23$, $p = 0.07$), with a tendency for target-absent RTs to increase more steeply with display size than target-present RTs (DS effects of 16 versus 10 ms per item).

2.3 *Discussion*

Experiment 1 yielded a pattern of performance that is consistent with previous reports (Davis and Driver 1994; Gurnsey et al 1996; Conci et al 2007b): search was efficient, with a search rate of 10 [16] ms per item on target-present [target-absent] trials. This search rate is near-identical to that observed in experiment 1 of Conci et al (2007b), in which comparable displays were used. Consequently, this outcome supports the view that search for a Kanizsa square can be performed with relative efficiency at parallel stages of processing (Davis and Driver 1994).

3 Experiment 2

Experiment 1 replicated previous reports in showing efficient search for a Kanizsa square configuration. Experiment 2 was identical to experiment 1, except that the shapes of targets and non-targets were modified: instead of squares used in experiment 1, observers were presented with triangle configurations. Given that previous studies reported inefficient search for Kanizsa triangles (Grabowecky and Treisman 1989; Grabowecky et al 1997), a similar outcome was expected in experiment 2.

3.1 *Method*

Eight observers (three male, mean age = 26.9 years, all with normal or corrected-to-normal vision) participated in experiment 2, which was identical to experiment 1, except that the square configurations were replaced by triangle target (figure 1b, T) and non-target (figure 1b, NT) configurations. Each triangle configuration was composed of three inducing elements, of a 1 deg diameter, arranged in an upward-pointing, triangular form. Triangles were equilateral, with each side of the configuration subtending 2.9 deg of visual angle, similar to experiment 1. An example display is shown in figure 2b.

3.2 *Results*

Erroneous responses were again quite rare (3.5% of all trials; 4.2% misses, 2.8% false alarms)—see figure 3b for the mean correct RTs, and the associated error rates, presented as a function of display size. As for experiment 1, an ANOVA was conducted on the error rates, with the factors target and display size. This analysis again revealed a marginally significant main effect of target and a significant interaction (T: $F_{1,7} = 5.07$, $p = 0.06$; T × DS: $F_{2,14} = 4.43$, $p < 0.04$); target misses were more frequent, and increased with display size, compared with the false alarms.

Next, the mean correct RT data were examined by means of a T × DS ANOVA which revealed all effects to be significant (T: $F_{1,7} = 35.19$, $p < 0.001$; DS: $F_{2,14} = 23.95$, $p < 0.001$; T × DS: $F_{2,14} = 13.02$, $p < 0.001$). Target-absent RTs were slower than target-present RTs, and RTs increased with display size, with a steeper increase for target-absent than for target-present RTs (DS effects of 50 versus 25 ms per item).

Finally, differences in search performance between square and triangle configurations were examined by comparing experiments 1 and 2 in a mixed-design ANOVA, with the between-subject factor experiment and the within-subjects factors target and display size.

This analysis revealed significant effects for both within-subjects factors and their interaction (T: $F_{1,14} = 60.89$, $p < 0.001$; DS: $F_{2,28} = 38.16$, $p < 0.001$; T × DS: $F_{2,28} = 15.17$, $p < 0.001$)—owing to a pattern already described above. More importantly, there were significant interactions of experiment with display size and target (experiment × DS: $F_{2,28} = 8.66$, $p < 0.001$; experiment × T × DS: $F_{2,28} = 5.28$, $p < 0.05$)—owing to the search rates (in particular for target-absent trials) being slower in experiment 2 than in experiment 1 (overall DS effects of 37 versus 13 ms per item). A direct comparison of the overall search rates (collapsed across target-present, positive and target-absent, negative trials) in experiments 1 and 2 revealed detection of a Kanizsa square to be more efficient than detection of a Kanizsa triangle ($t_{14} = 3.42$, $p < 0.003$). The same was true for separate comparisons of the positive-trial ($t_{14} = 3.17$, $p < 0.003$) and negative-trial ($t_{14} = 3.32$, $p < 0.003$) slopes, suggesting that the differential search efficiency between square and triangle configurations comes about because of the processes involved in the encoding of target-specific information on positive-trials (rather than simply in rejecting distractor-related information on negative trials).

3.3 *Discussion*

Experiment 2 replicated previous findings in showing that search for a Kanizsa triangle configuration involves serial scanning of display items (Grabowecky and Treisman 1989; Grabowecky et al 1977). Search for a Kanizsa triangle exhibited search rates that were about three times slower than search rates for a comparable Kanizsa square. In addition, the slope ratio between target-absent and target-present responses was increased for triangles (2 : 1) compared with squares (1.6 : 1). These differences support the view that not all illusory figures are detected with equal efficiency.

A possible reason for the differential search performance is that oblique shape orientations are processed less efficiently (slower) than corresponding cardinal orientations (Appelle 1972). While an influence of the 'oblique effect' has already been reported for other types of illusory figures (Purghe 1989; Ehrenstein and Hamada 1995), another critical difference could be the figural complexity of the stimulus configurations. For instance, the possible rotations and reflections of a stimulus configuration (R&R operations—Garner and Clement 1963) would yield higher complexity scores for triangles (R&R = 4) than for squares (R&R = 1). Given that complexity has been shown to critically influence search performance (Rauschenberger and Yantis 2006), a similar influence could explain the differential search efficiency with Kanizsa squares and triangles. Importantly, on this view, search for triangles would be inefficient because triangle configurations are more complex relative to squares in terms of their rotational and reflectional properties, and not because they possess oblique contours. To decide between these two alternative explanations, we carried out experiment 3 to investigate whether shape orientation would affect search efficiency even when controlling for alternative influences reflecting stimulus complexity (in terms of the R&R operations—see Shi and Elliott 2007, for a discussion of other indices of geometric complexity).

4 Experiment 3

Experiment 3 was designwise identical to experiments 1 and 2, except that the shapes of targets and non-targets were modified: instead of square and triangle configurations observers were presented with diamond configurations. Diamond configurations were similar in size and complexity to the square configurations, but presented an oblique orientation of the square.

4.1 *Method*

Eight observers (one male, mean age = 26.5 years, all with normal or corrected-to-normal vision) participated in experiment 3, which was identical to experiment 1, except that the square configurations were replaced by diamond target (figure 1c, T) and non-target configurations (figure 1c, NT). Diamonds were generated by rotating the square groupings of experiment 1 by 45°. An example display is shown in figure 2c.

4.2 *Results*
As with previous experiments, erroneous responses were rare (2.8% of all trials; 3.3% misses, 2.4% false alarms)—see figure 3c for the mean correct RTs, and the associated error rates, presented as a function of display size. Again, for experiment 3, the error rates were analysed by means of a target × display size ANOVA which did not reveal any significant effects (all ps < 0.16).

The mean correct RT data were examined by an ANOVA with identical design. This revealed all effects to be significant (T: $F_{1,7} = 149.97$, $p < 0.001$; DS: $F_{2,14} = 49.56$, $p < 0.001$; T × DS: $F_{2,14} = 5.29$, $p < 0.02$). Target-present RTs were faster than target-absent RTs, and RTs increased with display size, with a steeper increase for target-absent than for target-present RTs (DS effects of 27 versus 19 ms per item).

In addition, differences in RT performance between square and diamond configurations were explored by comparing experiments 1 and 3 in a mixed-design ANOVA, with the between-subject factor, experiment, and the within-subjects factors, target and display size. This analysis revealed significant effects for both within-subjects factors and their interaction (T: $F_{1,14} = 105.45$, $p < 0.001$; DS: $F_{2,28} = 67.55$, $p < 0.001$; T × DS: $F_{2,28} = 8.49$, $p < 0.001$)—owing to a pattern of effects described above. More importantly, there was also a significant interaction of experiment with display size (DS × Experiment: $F_{2,28} = 5.13$, $p < 0.02$), owing to overall slower search rates in experiment 3 compared to experiment 1 (DS effects of 23 versus 13 ms per item). Note that the experiment × display size interaction was also significant in an ANOVA of the target-present RTs only ($F_{2,28} = 7.41$, $p < 0.004$), with search rates of 19 ms in experiment 3 and 10 ms in experiment 1. A direct comparison of the overall search slopes (collapsed across positive and negative trials) in experiments 1 and 3 confirmed that detection of a Kanizsa square is more efficient than detection of a Kanizsa diamond ($t_{14} = 2.72$, $p < 0.009$). This was also true for separate comparisons of the slopes for positive and negative trials (positive trials: $t_{14} = 2.96$, $p < 0.05$; negative trials: $t_{14} = 2.09$, $p < 0.03$), suggesting that the increased efficiency for square, as compared to diamond, configurations is specifically related to the encoding of target attributes (rather than just the rejection of non-target attributes).

Finally, differences in RT performance between diamond and triangle configurations were examined by comparing experiments 2 and 3 in a mixed-design ANOVA. This again revealed significant effects for both within-subjects factors and their interaction (T: $F_{1,14} = 91.92$, $p < 0.001$; DS: $F_{2,28} = 53.36$, $p < 0.001$; T × DS: $F_{2,28} = 16.49$, $p < 0.001$), mirroring the pattern described above. More importantly, the factor experiment also showed (marginally) significant interactions with display size and target and display size (DS × experiment: $F_{2,28} = 2.28$, $p = 0.07$; target × DS × experiment: $F_{2,28} = 4.13$, $p < 0.03$), with search rates (in particular for target-absent trials) being slower in experiment 2 than in experiment 3 (DS effects of 37 versus 23 ms per item). This difference between configurations was again confirmed by a direct comparison of the overall search slopes between experiments 2 and 3, which revealed the difference to be significant ($t_{14} = 1.96$, $p < 0.04$). Separate comparisons of the positive-trial and negative-trial slopes showed a significant advantage for diamond, relative to triangle, configurations only for negative trials ($t_4 = 2.27$, $p < 0.02$), not for positive trials ($t_{14} = 1.08$, $p = 0.29$), suggesting that non-target information may be more easily excluded from search with diamond distractors. In summary, search for diamonds yielded a more efficient pattern of performance than search for triangles, but a less efficient pattern than search for squares.

4.3 *Discussion*

Experiment 3 revealed a pattern of results that suggests an intermediate efficiency of search for a diamond configuration (DS effects of 23 ms per item): search was less efficient than search for a square configuration (experiment 1, DS effects of 13 ms per item), but more efficient than search for a triangle configuration (experiment 2, DS effects of 37 ms per item).

The reduced efficiency for diamonds relative to squares is consistent with an influence of stimulus orientation on search: the oblique orientation of contours in diamonds (and triangles) negatively affects performance for both real (Appelle 1972) and illusory (Purghe 1989; Ehrenstein and Hamada 1995) figures. However, a comparison between diamond and triangle configurations revealed a second influence on search likely attributable to stimulus complexity (see Rauschenberger and Yantis 2006): search for a complex stimulus configuration (experiment 2, triangles: R&R = 4) was less efficient than search for a simple configuration (experiment 3, diamonds: R&R = 1). Consistent with Rauschenberger and Yantis (2006), this effect of complexity was most marked for target-absent trials, reflecting a difficulty in excluding more complex distractors from search. Thus, both the orientation of the search-critical shape and the stimulus complexity contribute to the efficiency of search for illusory figures.

5 General discussion

The experiments described here were designed to re-investigate shape completion in search for Kanizsa figures. The results demonstrate that orientation is a crucial factor in figural completion: cardinal shape orientations (square configurations) were processed more efficiently than oblique orientations (triangle and diamond configurations), suggesting differential completion rates for illusory figures. Furthermore, search efficiency was found to decrease as stimulus complexity increased: stimulus configurations that scored higher in terms of their rotational and reflectional properties (triangles: R&R = 4) were detected less efficiently than more regular configurations (squares and diamonds: R&R = 1).

Experiment 1 was intended to replicate previous reports of efficient search for a Kanizsa square target among comparable square non-targets (Davis and Driver 1994; Gurnsey et al 1996; Conci et al 2007b). Consistent with previous studies, Kanizsa squares were detected almost equally efficiently regardless of display size, with a search rate (mean DS effect) of 10 [19] ms per item for target-present [target-absent] trials (see also Conci et al 2007b). Search rates of this order may be taken to suggest that Kanizsa squares are detected as groupings, with detection based directly on the preattentive and parallel coding of the search display. By contrast, detection of a Kanizsa triangle target among comparable triangular non-targets was revealed to be less efficient in experiment 2, with search rates (mean DS effect of 25 [50] ms per item for target-present [target-absent] trials) in a range taken to be indicative of search involving attentional processing. This finding is in agreement with previous reports of inefficient search for Kanizsa triangles (Grabowecky and Treisman 1989; Grabowecky et al 1997). Finally, to investigate whether the decrease in performance with Kanizsa triangle, compared to square, targets can be attributed to influences of shape orientation (oblique versus cardinal), in experiment 3 we examined search for a Kanizsa diamond. The diamond was chosen as target stimulus (presented among comparable non-target stimuli) because it differed from a square only in terms of its orientation (oblique), while controlling for alternative influences of stimulus size and complexity. The results revealed search efficiency (mean DS effects of 19 [27] ms per item on target-present [target-absent] trials) to be intermediate between square and triangle targets. The differential performance in experiment 3 relative to experiment 1 (diamond versus square configurations) can be ascribed to the 'oblique effect', while the differential performance in experiment 3 relative to experiment 2 (diamond versus triangle configurations) can be attributed to stimulus complexity (which is higher for triangles than for diamonds).

5.1 *Oblique effect*

The difference in performance between cardinal and oblique shape orientations reveals an oblique effect in the detection of Kanizsa figures: horizontal and vertical orientations (in experiment 1) are processed more efficiently than oblique orientations (in experiments 2 and 3). This is consistent with previous observations of an oblique effect in real (Appelle 1972) and illusory objects, such as in the Ehrenstein grid (Purghe 1989) and the Ebbinghaus illusion (Ehrenstein and Hamada 1995). The presence of an oblique effect in Kanizsa-figure search raises the question which attribute of the illusory figure is sensitive to orientation.

One 'minimal' attempt to account for the oblique effect revealed in the present study would be to assume that search is based on the output of simple, non-oriented blob detectors, and variations in search efficiency arise because oblique edges add more noise to the decision process than horizontal and vertical edges. However, while offering a basic candidate mechanism, the assumption of different levels of decision noise does not easily account for the search rate difference between cardinal and oblique shape orientations, which may be taken to reflect a qualitative difference in performance (efficient versus inefficient search). Therefore, arguably, more elaborate processes of object integration would have to be considered that explain the variation of search performance as a function of stimulus orientation, reflecting specific figural attributes of an illusory object.

There is convergent evidence that, for Kanizsa figures, illusory contours are not encoded preattentively (Gurnsey et al 1996; Conci et al 2007b; X Li et al 2008), in contrast with illusory contours generated by offset gratings (Gurnsey et al 1992; X Li et al 2008). Instead, search appears to be performed primarily on the basis of a relatively crude surface representation with surface filling-in processes guiding search (Stanley and Rubin 2005; Conci et al 2006, 2007b). On this evidence, the present results are not to be understood in terms of differences in search emerging because of variations in the efficiency of computing the orientation of an illusory contour, as suggested by Davis and Driver (1994). Instead, cardinal and oblique orientations appear to differ in efficiency for processes of region extraction in Kanizsa figures. In agreement with the suggestion that mechanisms of global surface extraction are sensitive to shape orientation, Purghe (1989) showed that brightness filling-in elicits an oblique effect in the Ehrenstein grid. Accordingly, the current experiments demonstrate that the global orientation of the illusory surface has a crucial influence on search efficiency.

Variations in performance with stimulus orientation have typically been associated with a differential number of neural analysers tuned to the various orientations (Appelle 1972). Recently, neurophysiological studies have revealed that neurons in V1 exhibit asymmetries in the response profile, with cardinal orientations producing larger responses than oblique orientations (Furmanski and Engel 2000; B Li et al 2003). Asymmetric response profiles have also been reported for extrastriate cortical regions (Wang et al 2003) and inferior temporal cortex (Orban and Vogels 1998), suggesting that the regions typically involved in the processing of illusory Kanizsa figures (see Seghier and Vuilleumier 2006, for review) show a comparable asymmetric distribution of responses with variations of orientation. Moreover, the unequal distribution of orientation preference and selectivity in simple cells in V1 has been suggested to disproportionately affect the subsequent input to complex cells and higher-order cortical areas (B Li et al 2003).

In sum, an explanation why oblique shapes are detected less efficiently than cardinal shapes might be twofold. On the one hand, oblique object integration is less efficient because fewer neuronal analysers contribute to the computation of region information in search-critical areas along the ventral stream. Thus, the orientation-specific difference in detection rates might be directly explained by the nonpreferred oblique-shape integration of the illusory figure (as opposed to preferred orthogonal-shape integration). However, a second influence could also relate to a disadvantage for oblique shapes arising from deficiencies in computing oblique inducers at early levels of processing (eg in area V1): on this view, encoding of the physical stimulus edges would be less stable with oblique (relative to cardinal) orientations, as a result of which the subsequent extraction of the illusory figure would be less reliable and search guidance less efficient. As demonstrated by B Li et al (2003), both aspects influence processing at the neuronal level, and, consequently, both could potentially impact on search. However, the oblique effect in the current study was specifically related to the processing of target attributes (see experiment 3). This may be taken to indicate that oblique orientations have an effect predominantly at the level of surface filling-in, rather than encoding of the physically specified inducers (since an oblique effect at the inducer level should affect positive and negative responses to an equal extent).

5.2 *Complexity effect*

A second factor influencing detection performance in the present experiments relates to the complexity of the stimulus configurations. As reported previously for dot patterns (Rauschenberger and Yantis 2006), an increase in stimulus complexity can result in a decrease in search efficiency. Analogously, search for more complex Kanizsa triangles was found to be performed less efficiently than search for more regular Kanizsa squares or diamonds, suggesting that complexity provides an additional influence (beside shape orientation) affecting the efficiency of target detection. According to the framework proposed by Rauschenberger and Yantis (2006), search is performed on the basis of whole-scene representations, with the complexity of stimulus configurations determining how efficiently a given scene is encoded. In accordance with this proposal, the efficiency of detecting a Kanizsa figure would depend on the time required to extract relatively crude regions within a given display, with more complex configurations taking longer to be encoded. Region extraction is likely to involve processes that seek to determine contiguous image regions by means of signal propagation (cf Stanley and Rubin 2005)—which would take more time for configurations that are more complex and less symmetrical, because these would involve a greater degree of non-convergent signal propagation (ie signal propagation in one direction not being met by propagation from the opposite direction). This could explain why variations in complexity would give rise to differential performance in search for Kanizsa figures.

An alternative interpretation (which is not necessarily incompatible with that outlined above) may be based on the fact that the influence of complexity was particularly pronounced for display configurations without target (see comparison of negative slopes between experiments 2 and 3)—suggesting that, in line with Rauschenberger and Yantis (2006), complexity affects particularly the efficiency of rejecting distractors as non-targets, possibly because more complex distractor configurations add more noise to the decision process than regular configurations.

In conclusion, the present results suggest that not all Kanizsa figures are detected with equal efficiency. Rather, the orientation of the global illusory surface is integrated and, thus, detected more efficiently when it is oriented on a vertical or horizontal axis, compared to diagonal axes. In addition, stimulus complexity was shown to also have a significant impact on the search rates, with processing being less efficient for displays with complex, as compared to regular, configurations. This complex interplay of different figural aspects in visual search suggests that the extracting of illusory figures is reliant upon a variety of processes that dynamically adjust performance to effectively integrate fragmentary information.

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References

Appelle S, 1972 "Perception and discrimination as function of stimulus orientation: The oblique effect in man and animals" *Psychological Bulletin* **78** 266 – 278

Conci M, Gramann K, Müller H J, Elliott M A, 2006 "Electrophysiological correlates of similarity-based interference during detection of visual forms" *Journal of Cognitive Neuroscience* **18** 880 – 888

Conci M, Müller H J, Elliott M A, 2007a "Closure of salient regions determines search for a collinear target configuration" *Perception & Psychophysics* **69** 32 – 47

Conci M, Müller H J, Elliott M A, 2007b "The contrasting impact of global and local object attributes on Kanizsa figure detection" *Perception & Psychophysics* **69** 1278 – 1294

Davis G, Driver J, 1994 "Parallel detection of Kanizsa subjective figures in the human visual system" *Nature* **371** 291 – 293

Donnelly N, Humphreys G W, Riddoch M J, 1991 "Parallel computation of primitive shape descriptions" *Journal of Experimental Psychology: Human Perception and Performance* **17** 561 – 570

Duncan J, Humphreys G W, 1989 "Visual search and stimulus similarity" *Psychological Review* **96** 433 – 458

Ehrenstein W H, Hamada J, 1995 "Structural factors of size contrast in the Ebbinghaus illusion" *Japanese Psychological Research* **37** 158 – 169

Furmanski C S, Engel S A, 2000 "An oblique effect in human primary visual cortex" *Nature Neuroscience* **3** 535 – 536

Garner W R, Clement D E, 1963 "Goodness of pattern and pattern uncertainty" *Journal of Verbal Learning and Verbal Behavior* **2** 446 – 452

Grabowecky M, Treisman A M, 1989 "Attention and fixation in subjective contour perception" *Investigative Ophthalmology and Visual Science* **30** 457

Grabowecky M, Yamada S, Strode C, 1997 "All Kanizsa contours are not created equal: Visual search for subjective shapes" *Abstracts of the Psychonomic Society* **2** 2

Grossberg S, Mingolla E, 1985 "Neural dynamics of form perception: Boundary completion, illusory figures and neon colour spreading" *Psychological Review* **92** 173 – 211

Gurnsey R, Humphrey G K, Kapitan P, 1992 "Parallel discrimination of subjective contours defined by offset gratings" *Perception & Psychophysics* **52** 263 – 276

Gurnsey R, Poirier F J A M, Gascon E, 1996 "There is no evidence that Kanizsa-type subjective contours can be detected in parallel" *Perception* **25** 861 – 874

Heydt R von der, Peterhans E, Baumgartner G, 1984 "Illusory contours and cortical neuron responses" *Science* **224** 1260 – 1262

Kanizsa G, 1955 "Margini quasi-percettivi in campi con stimolazione omogenea" *Rivista di Psychologia* **49** 7 – 30

Koffka K, 1935 *Principles of Gestalt Psychology* (New York: Harcourt)

Li B, Peterson M R, Freeman R D, 2003 "Oblique effect: A neural basis in visual cortex" *Journal of Neurophysiology* **90** 204 – 217

Li X, Cave K, Wolfe J M, 2008 "Kanizsa-style subjective contours do not guide attentional deployment in visual search but line-termination contours do" *Perception & Psychophysics* **70** 477 – 488

Orban G A, Vogels R, 1998 "The neural machinery involved in successive orientation discrimination" *Progress in Neurobiology* **55** 117 – 147

Pomerantz J R, Sager L C, Stoever R J, 1977 "Perception of wholes and of their component parts: Some configural superiority effects" *Journal of Experimental Psychology: Human Perception and Performance* **3** 422 – 435

Purghe F, 1989 "Privileged directions for subjective contours: horizontal and vertical versus tilted" *Perception* **18** 201 – 213

Rauschenberger R, Yantis S, 2006 "Perceptual encoding efficiency in visual search" *Journal of Experimental Psychology: General* **135** 116 – 131

Rensink R A, Enns J T, 1995 "Preemption effects in visual search: Evidence for low-level grouping" *Psychological Review* **102** 101 – 130
Seghier M L, Vuilleumier P, 2006 "Functional neuroimaging findings on the human perception of illusory contours" *Neuroscience and Biobehavioral Reviews* **30** 595 – 612
Shi Z, Elliott M A, 2007 "Oscillatory priming and form complexity" *Perception & Psychophysics* **69** 193 – 208
Stanley D A, Rubin N, 2005 "Rapid detection of salient regions: Evidence from apparent motion" *Journal of Vision* **5** 690 – 701
Wang G, Ding S, Yunokuchi K, 2003 "Difference in the representation of cardinal and oblique contours in cat visual cortex" *Neuroscience Letters* **338** 77 – 81
Wertheimer M, 1923 "Untersuchungen zur Lehre von der Gestalt" *Psychologische Forschung* **4** 301 – 350 [Translation into English published in Ellis W, 1938 *A Source Book of Gestalt Psychology* (London: Routledge & Kegan Paul) pp 71 – 78]

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