Surface filling-in and contour interpolation contribute independently to Kanizsa figure formation

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Abstract (200)

To explore mechanisms of object integration, the present experiments examined how completion of illusory contours and surfaces modulates the sensitivity of localizing a target probe. Observers had to judge whether a briefly presented dot probe was located inside or outside the region demarcated by inducer elements that grouped to form variants of an illusory, Kanizsa-type figure. From the resulting psychometric functions, we determined observers' discrimination thresholds as a sensitivity measure. Experiment 1 showed that sensitivity was systematically modulated by the amount of surface and contour completion afforded by a given configuration. Experiments 2 and 3 presented stimulus variants that induced an (occluded) object without clearly defined bounding contours, which gave rise to a relative sensitivity increase for surface variations on their own. Experiments 4 and 5 were performed to rule out that these performance modulations are simply attributable to variable distances between critical local inducers, or to costs in processing an interrupted contour. Collectively, the findings provide evidence for a dissociation between surface and contour processing, supporting a model of object integration in which completion is instantiated by feedforward processing that independently renders surface filling-in and contour interpolation and a feedback loop that integrates these outputs into a complete whole.

Keywords: Kanizsa figure, illusory contours, surface filling-in, modal completion, amodal completion

Public Significance Statement

One of the fundamental operations of human vision concerns the identification of relevant perceptual units, or objects that are present in the visual ambient array. A prime example to demonstrate such mechanisms of object integration is the Kanizsa figure, which illustrates that separate parts may be effectively bound to represent a coherent whole. This study was performed to investigate complementary mechanisms underlying object completion, namely the extraction of a bounding contour and its concurrent estimation of the surface area in perceiving a coherent Kanizsa figure. In a series of experiments, illusory figure sensitivity was measured using a dot-localization task while contrasting the relative impact of contour and surface completion mechanisms. We show that both contour and surface completions substantially impact illusory figure sensitivity, but importantly, both processes of object completion appear to operate relatively independent of each other, which has implications for models of object integration.

Introduction

Detecting the boundaries of objects is a fundamental task of early vision, so as to identify the available perceptual units, or objects, and segment these from other objects and from the background (Cornsweet, 1970; Marr, 1982). In many situations, object perception occurs despite degraded ambient luminance conditions, attesting to a remarkable capability of the visual system to integrate separate fragments into coherent wholes. This is illustrated in various examples of illusory figures (Kanizsa, 1955), where the presentation of 'pacman'-type inducer elements gives rise to the perception of illusory objects. For example, in Figure 1 (Kanizsa), a diamond-shape object is perceived to occlude neighboring parts of four circular elements, despite physically homogenous luminance across the diamond and background. Such a perceptual 'filling-in' of an object, accompanied by a concurrent brightness enhancement of the filled-in surface, is referred to as 'modal completion'.

It is commonly assumed that the mechanisms underlying such completion phenomena reflect the interpolation of the missing parts of the bounding contours and the filling-in of the surface of the enclosed area (Grossberg & Mingolla, 1985; Pessoa, Thompson, & Noë, 1998; Kogo, Strecha, Van Gool, & Wagemans, 2010). For instance, results from neurophysiological recordings suggest that the filling-in process, which generates the perception of an illusory surface, is associated with activations in the lateral occipital complex (LOC) and the fusiform gyrus (e.g., Stanley & Rubin, 2003; Bakar, Liu, Conci, Elliott, & Ioannides, 2008), while boundary completion is accomplished in both V1 and V2 (Lee & Nguyen, 2001; Von Der Heydt, Peterhans, & Baurngartner, 1984) and to some extent also in the LOC (Shpaner, Stanley, Rubin, & Foxe, 2004; Murray, Imber, Javitt, & Foxe, 2006). Together, these findings suggest that separate regions in the ventral visual processing stream make distinct functional contributions to the perception of illusory figures (Seghier & Vuilleumier, 2006, for a review). The present study aimed at determining the relative contributions of such contour and surface completion mechanisms in forming the percept of an illusory figure.

Recent behavioral studies have used the visual search paradigm to systematically examine the role of surface and contour processing in variations of Kanizsa figures. To this end, configurations were generated that either presented an illusory Kanizsa figure (Figure 1, Kanizsa), or a symmetric configuration that does not induce an illusory shape (Figure 1, Baseline). Additional configurations induced ‘partial’ groupings, that is, either a partial illusory contour (Figure 1, Contour) or a partial contour-plus-surface arrangement (Figure 1, Shape). Conci, Müller, and Elliott (2007a) presented such configurations in a visual search task to investigate how surface and contour grouping in distractors would modulate detection of a Kanizsa target shape. They found that the partial surface, but not the presence of contours in distractors, modulates the efficiency with which a Kanizsa target square is detected (see also Conci, Gramann, Müller, & Elliott, 2006; Nie, Maurer, Müller, & Conci, 2016). This suggests that the selection of an illusory figure primarily relies on processes of surface filling-in. In this view, visual search with illusory figures is largely guided by a crude specification of a closed target shape, without requirement to compute the exact contours of the respective objects. However, the type of search task used in this study (see Davis & Driver. 1994) likely only requires a relatively broad tuning of attention to a target (Kanizsa) shape, so that it might, in fact, underestimate the role of contour interpolation. By contrast, studies of neuropsychological patients with visual neglect (Vuilleumier & Landis, 1998; Vuilleumier, Valenza, & Landis, 2001) indicate that contour completion can also determine attentional selection, thereby reducing extinction behavior. This suggests that both the filling-in of surfaces and the interpolation of the bounding contours might be accomplished at early stages of visual processing, thus guiding attention to potential target locations.

To directly measure illusory figure completion, Stanley and Rubin (2003) used a psychophysical method that allows perceptual sensitivity to be determined in a dot-localization task (see also Guttman & Kellman, 2004). The task involved the localization of a dot probe, which was presented briefly near a presumed illusory edge in a Kanizsa figure configuration. Observers were asked to decide whether the presented dot appeared inside or outside the region demarcated by the Kanizsa figure. Performance in this task was then used to determine psychometric functions, with their slope parameter characterizing the dot-localization sensitivity. Stanley and Rubin showed that the sensitivity in localizing the dot was significantly higher for an illusory (Kanizsa) figure than for a configuration that presented a closed region without concurrent illusory contour. Using a roughly similar method (but without explicitly quantifying sensitivity), it has also been shown that detection of a target dot is more efficient inside an illusory edge of a Kanizsa figure than outside (Ricciardelli, Bonfiglioli, Nicoletti, & Umiltá, 2001). Together, these findings suggest that the perceptual sensitivity in the dot-localization task can provide an indirect measure of grouping strength, with the Kanizsa figure being associated with a higher sensitivity than a comparable configuration without illusory object.

To further investigate how contours and surfaces influence the completion of Kanizsa figures, the current study presented configurations that allow for a dissociation of the respective surface and contour portions of a grouped figure (see Conci et al., 2006; 2007a) using the dot-localization task (Stanley & Rubin, 2003) in a series of psychophysical experiments. The configurations that were presented in the experiments were characterized by a graded amount of surface and contour in variants of Kanizsa figure configurations (see Figure 1): the Kanizsa diamond induces a complete illusory figure (Figure 1, Kanizsa), the 'Shape' configuration provides partial surface and contour information (Figure 1, Shape), and the 'Contour' configuration induces only a partial illusory contour (Figure 1, Contour); the 'Baseline' arrangement, by contrast, presents no grouped object (i.e., no illusory figure) while consisting of similar inducer elements and a symmetric arrangement (Figure 1, Baseline). The efficiency of illusory figure completion was measured by quantifying the discrimination in the inside/outside dot-localization task by determining psychometric functions for these four types of configuration. The discrimination threshold of the psychometric functions was then used as a measure of the perceptual sensitivity. Thus, comparing the perceptual sensitivity among the Kanizsa, Shape, Contour, and Baseline conditions permitted us to effectively assess how contour interpolation and surface filling-in processes contribute to the completion of an illusory figure.

Experiment 1

Experiment 1 was performed to measure the contribution of surface and contour completions in illusory figure perception, by employing a dot-localization task in which observers had to decide whether a target dot was located inside or outside a region demarcated by the inducer elements of a Kanizsa-type configuration (see also Stanley & Rubin, 2003, and Figure 1 for possible types of configuration). The discrimination threshold of dot-localization performance estimated from the psychometric function was taken as a measure of the perceptual sensitivity for a given configuration, thus permitting us to assess how surface filling-in and contour interpolation modulate the perceptual sensitivity.

Method

Participants. Twelve right-handed volunteers (8 men; mean age: 23.42 ± 1.98 years) with normal or corrected-to-normal visual acuity participated in the experiment for payment of €8.00 per hour. All participants provided written informed consent, and the experimental procedure was approved by the ethics committee of the Department of Psychology, Ludwig-Maximilians-Universität München. The sample size was determined on the basis of previous, comparable studies (e.g., Stanley & Rubin, 2003), aiming for 80% power to detect a relatively large effect size (f=.4; cf. Cohen, 1988) when using a repeated-measures ANOVA (within-factors, 4 conditions) with an alpha level of .05. Power estimates were computed using G*Power (Erdfelder, Faul, & Buchner, 1996). It should be noted that studies, which compute psychometric functions tend to conventionally test rather small samples, often with less than ten observers (e.g. Shi & Nijhawan, 2008; Hickok, Farahbod, & Saberi, 2015), but at the same time seek to thoroughly characterize performance for each subject using many trials with rather fine-grained measurement steps in order to determine a rather precise sensitivity estimate.

Apparatus and Stimuli. The experiment was conducted in a sound-attenuated room that was dimly lit with indirect, incandescent lighting. Stimuli were generated with an IBM-PC compatible computer using Matlab routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997), and were presented in light gray (1.83 cd/m^2) against a black (0.02 cd/m^2) background at the center of a 17-inch monitor screen (1024×768 pixels screen resolution, 85-Hz refresh rate). There were four types of experimental stimuli (see Figure 1): (1) a Kanizsa-type diamond shape (Kanizsa), (2) a shape configuration that depicted partial contour and surface completions (Shape), (3) a configuration that only induced an illusory contour without an associated surface (Contour), and (4) a control configuration that consisted of four outward-facing ‘pacman’ inducers, revealing a symmetric arrangement but without any emerging shape (Baseline). Each pacman inducer subtended a visual angle of 1.1°. The radius of the illusory diamond shape in the Kanizsa figure configuration was 3.7° of visual angle. The ‘support ratio’ (Banton & Levi, 1992), that is, the ratio between the luminance-defined portion and the completed illusory contour, was 0.4.

Figure 1 about here

Procedure. Observers performed a dot-localization task. Each trial started with the presentation of a central fixation cross for 250 ms, followed by a 750-ms pre-cue display that presented four disks in a diamond arrangement around the central fixation cross. Next, one of the four configuration conditions (Kanizsa, Shape, Contour or Baseline) was briefly presented for 150 ms, after which a (target) dot probe (with a diameter of 8.3 arc-min) was added to the display and presented for another 100 ms near the bottom left or right illusory edge of a given pacman configuration. The dot probe appeared randomly at one of ten equidistant locations within a range of -53 to 53 arc-min along the midline perpendicular to the bottom left or right border of the illusory figure (see Figure 2A for possible dot locations). Observers indicated whether the dot probe was located inside or outside of the region enclosed by the inducers, by pressing the left or the right button on a computer mouse, respectively. To ensure that observers correctly performed the task, detailed instructions were provided (https://osf.io/3ydju/), which also included illustrations of the correct boundary that determines the inner region of the configuration (see green lines in Figure 1, bottom panels). Note that the boundary of a given configuration was always located at the very same position on the screen for all types of configuration. On a given trial, observers were instructed to fixate the central fixation cross. The relatively short duration of the dot probe (100 ms) ensured that observers could not make eye movements towards it. An example trial sequence is shown in Figure 2B.

Figure 2 about here

Every participant completed 8 blocks of 100 trials each, resulting in 800 trials in total. Every block presented one of the four configurations (Kanizsa, Shape, Contour, and Baseline) with the dot appearing either in the lower left or the lower right quadrant of the stimulus in separate blocks, with randomized block order across participants. Note that we probed the lower left and right quadrants of the display because the lower hemifield has been shown to produce a stronger percept of illusory figures than the upper hemifield (Rubin, Nakayama, & Shapley, 1996). In each block, a given configuration was presented with ten possible dot locations in a given quadrant across ten repetitions. For the analysis, the data from the left and right dot-presentation quadrants were collapsed. Before the experiment, every participant was acquainted with the task in a block of 16 practice trials.

The fraction of 'out' responses was plotted against the relative dot position. These data were fitted with a psychometric function $0.5\times[1 + \gamma\times tanh(0.745(x-\beta)/\alpha)]$, where α is the discrimination threshold defined as stimulus increment from β (the Point of Subjective Equivalence, PSE) to reach 82% performance (see Stanley & Rubin 2003), and γ reflects the performance range. Note that the discrimination threshold α is inversely related to the slope of the psychometric function (the slope at the PSE is $0.3725/\alpha$) and thus gives an indication of the precision, while the PSE β defines the accuracy.

Results

The results of Experiment 1 are depicted in Figure 3A. The psychometric curves show the across-observer average fraction of 'out' responses as a function of dot position (upper panel). The numbers on the x-axis denote the relative distances from the objective boundary of the configuration, with positive values corresponding to "outside" dot locations and negative values to "inside" locations (see Figure 3A; a value of zero would correspond to the location of the boundary). The corresponding slopes of the curves provide an estimate of the sharpness of the perceived illusory figure. We defined the discrimination threshold as the dot displacement needed to shift responses from 50% to 82% ‘out’ (see Methods above). The lower panel in Figure 3A displays the corresponding mean discrimination thresholds (α) across observers in the four conditions. To determine whether there were differences in the discrimination threshold of the psychometric functions across configurations, we performed a repeated-measures ANOVA with the factor configuration (Kanizsa, Shape, Contour, Baseline). We additionally report the estimated Bayes factors (BF_{10}) as revealed by comparable Bayesian statistics using JASP (Love et al., 2015). The Bayes factor provides the ratio with which the alternative hypothesis is favored over the null hypothesis (i.e., larger BFs argue in favor of the alternative hypothesis with values below 1 supporting the null hypothesis while values above 3 would indicate moderate -, and values above 10 strong evidence in favor of the alternative hypothesis; see Jeffreys, 1961; Kass & Raftery, 1995).

This analysis yielded a significant main effect, $F(3, 33) = 44.92$, $p < .0001$, $\eta_p^2 = .80$, 90% confidence interval, or CI [.67, .85], BF_{10} =6.25e+11. For the post-hoc comparisons, given that such repeated testing increases the chance of obtaining a significant effect, a Bonferroni correction was applied (Neter & Wasserman, 1974). Thresholds were lower in the Kanizsa condition ($M = 4.53$) compared to all other conditions (Shape vs. Kanizsa: $t(11) = 3.91$, $p = .015$, $d_z = 1.13$, 95% CI [.38, 1.84], $BF_{10} = 18.83$; Contour vs. Kanizsa: $t(11) = 6.45$, $p < .0001$, $d_z = 1.86$, 95% CI [.89, 2.80], $BF_{10} = 553.01$; Baseline vs. Kanizsa: $t(11) = 7.99$, $p < .0001$, $d_z = 2.31$, 95% CI [1.19, 3.40], $BF_{10} = 3109.71$). The Shape threshold ($M = 6.17$) was lower than the Contour and Baseline thresholds (Contour vs. Shape: $t(11) = 6.01$, $p = .001$, $d_z = 1.73$, 95% CI [.81, 2.63], BF_{10} =320.32; Baseline vs. Shape: $t(11) = 7.31$, $p < .0001$, $d_z = 2.11$, 95% CI [1.06, 3.13], BF_{10} =1489.78). Finally, the threshold for the Contour ($M = 9.95$) was lower than that for the Baseline ($M = 14.56$; $t(11) = -4.32$, $p =.007$, $d_z = -1.25$, 95% CI [-2.00, -.47], $BF_{10} = 33.86$).

According to Figure 3A (upper panel), the Point of Subjective Equivalence (PSE, 50%) appeared to be shifted leftwards from the objective contour location (‘0’), in particular for the Kanizsa condition. We therefore determined the PSE from the psychometric function (β). The deviation from the objective contour location was tested with a series of one-sample t-tests (2-tailed). Among the four configurations, only the Kanizsa figure showed a significant deviation from objective contour location (M = -3.13), $t(11) = -3.10$, $p = .01$, $d_z = -.90$, 95% CI [-1.56, -.21], $BF_{10} = 5.88$ (all other conditions, $ts(11) < .74$, ps > .48, all $d_z < .21$, all $BF_{10} < 0.36$). A potential interpretation of this deviation for the Kanizsa diamond might be that observers perceive the illusory contour as being curved towards the inside. Note that a comparable result was also obtained in Experiments 3–5 for the Kanizsa condition [$ts(11) < -3.01$, ps < .01, all $d_z < -.87$, all $BF_{10} > 5.15$].

Figure 3 about here

Discussion

The discrimination threshold of the psychometric function as derived from the dot-localization performance provides an estimate of the perceptual sensitivity, that is, the ‘sharpness’ of the perceived illusory figure. Experiment 1 characterized the effect of surface and contour information on the discrimination thresholds as determined from the psychometric functions. Our results suggest overall a high precision in measuring the perceptual sensitivity with the current procedure (all $\eta_p^2 > .14$, $|d| > .8$; $BF_{10} > 10$; see Cohen, 1988; Jeffreys, 1961). The threshold derived from these measurements revealed to be lowest for Kanizsa figures, followed by Shape and Contour configurations, indicating that the perceptual sensitivity is modulated by the amount of surface information present in the configuration, with higher sensitivity – as indicated by a decreased threshold and a steeper slope in the psychometric function – with more surface information. In addition, we also observed that contour information impacts the perception of the illusory shape, with a significantly decreased threshold for Contour as compared to Baseline configurations, illustrating that contours on their own can support efficient dot localization (see also Conci et al., 2009). This indicates that both surface and contour completions strengthen the perception of the illusory figure.

An additional analysis showed that the Kanizsa figure exhibited a significant deviation from the objective contour location (when assuming that the illusory contour renders a straight, linear boundary). This result is consistent with the view that the illusory contour is actually perceived as being somewhat curved towards the inside. Using Kanizsa triangles as test stimuli, Gintner, Aparajeya, Leymarie, and Kovács (2016) recently observed a comparable pattern of contour curvature towards the inside – a pattern in line with the current finding, indicating that the visual system ultimately represents illusory contours with less precision and accuracy than comparable luminance-defined contours (see also Guttman & Kellman, 2004). While the contours of the Kanizsa diamond were thus perceived as slightly curved, the same analysis of the PSE for the Baseline (and Shape as well as Contour conditions) revealed no reliable deviation from the objective contour location. This shows that participants did follow the instructions and responded based on the boundary at the same location in all configurations (i.e., as illustrated by the green lines in Figure 1).

Experiment 2

Experiment 1 revealed a graded reduction of the discrimination threshold from Baseline through Contour and Shape configurations to the Kanizsa diamond. A potential explanation of this pattern might be that the computation of both the illusory contours and the surface contributed to the change in precision. Alternatively, it might be the contour alone which leads to a performance difference, with stronger contour perception in the Kanizsa and Shape configurations compared to the Contour condition (i.e., with the object's surface enhancing the strength of the contour and thereby facilitating performance). To decide between these alternatives, Experiments 2 and 3 were performed to determine whether dot detection performance would also be modulated by other forms of completion that provide a comparable amount of surface filling-in, but without giving rise to a corresponding (illusory) contour.

For instance, besides modal completion, which was tested in Experiment 1, another, related grouping phenomenon is referred to as 'amodal completion', which occurs when an interpolated figure is perceived as lying behind an occluding object (see Figure 4A; Michotte, Thines, & Crabbe, 1964/1991; Kanizsa, 1979; see also

Chen, Müller & Conci, 2016; Chen, Töllner, Müller, & Conci, 2017). Figure 1 provides a typical example of modal completion: a Kanizsa diamond that induces a bright surface with illusory contours. In comparison, in the example depicted in Figure 4A, an integrated diamond is perceived as well, but it appears to be completed behind the four circular apertures. Thus, in this case, the diamond shape is completed behind the occluding region, and as a result, the illusory contour is not directly visible (see illustration in Figure 4A, and Michotte et al., 1964/1991). Thus, in the configurations in Figure 4B, surface completion remains to connect disparate parts of the figures (e.g., in the Kanizsa and Shape conditions), but there is no crisp boundary forming an illusory contour (e.g. in all configurations presented in Figure 4B).

Experiment 2 used a similar paradigm to that described for Experiment 1 and investigated how the dot-localization sensitivity is affected by amodal completion (as opposed to modal completion in Experiment 1), that is, when the illusory contours are not visible due to partial occlusion. If surface processing contributes to our performance measure and is dissociable from the completion of (illusory) contours, then perceptual sensitivity would be expected to be modulated by surfaces even when no precise bounding contour is available.

Method

Experiment 2 was basically identical to Experiment 1, with the following differences: 12 right-handed paid volunteers (7 men; mean age: 23.5 ± 2.15 years; normal or corrected-to-normal vision) participated in the experiment. Stimuli in Experiment 2 were designed to induce amodal completion. The stimulus arrangements were identical to those revealing modal completion in Experiment 1, except that a gray outline circle was added to surround each pacman inducer (line thickness: 9 arc-min; see Figure 4B).

Figure 4 about here

Results

The upper panel in Figure 3B displays the psychometric curves (averaged across observers) as a function of dot position, separately for the different configuration conditions. In addition, the lower panel of Figure 3B shows the corresponding mean discrimination thresholds. A repeated-measures ANOVA with the factor configuration (Kanizsa, Shape, Contour, Baseline)[1] again revealed a significant effect, $F(3, 33) = 20.76$, $p < .0001$, $\eta_p^2 = .65$, 90% CI [.44, .73], $BF_{10} = 9.43e+4$. The thresholds were lower for Kanizsa ($M = 12.63$) and Shape ($M = 13.62$) than for Contour ($M = 19.44$) and Baseline ($M = 18.55$) configurations (Contour vs. Kanizsa: $t(11) = 6.53$, $p < .0001$, $d_z = 1.88$, 95% CI [.91, 2.83], $BF_{10} = 603.42$; Baseline vs. Kanizsa: $t(11) = 4.44$, $p = .006$, $d_z = 1.28$, 95% CI [.49, 2.04], $BF_{10} = 40.29$; Contour vs. Shape: $t(11) = 9.01$, $p < .0001$, $d_z = 2.60$, 95% CI [1.38, 3.80], $BF_{10} = 8.64e+3$; Baseline vs. Shape: $t(11) = 4.33$, $p = .007$, $d_z = 1.25$, 95% CI [.47, 2.00], $BF_{10} = 34.27$). There were no significant threshold differences between Kanizsa and Shape, $t(11) = .87$, $p > .99$, $d_z = .25$, 95% CI [-.33, .82], $BF_{10} = 0.40$, or between Contour and Baseline configurations, $t(11) = .92$, $p > .99$, $d_z = .27$, 95% CI [-.32, .84], $BF_{10} = 0.41$.

A further analysis then compared all configurations across Experiments 1 and 2. To this end, we performed a mixed-design ANOVA with the within-subjects factor configuration and the between-subjects factor experiment. This analysis revealed a main effect of configuration, $F(3, 66) = 57.28$, $p < .0001$, $\eta_p^2 = .72$, 90% CI [.61, .77], $BF_{10} = 5.03e+13$, with lower thresholds for Kanizsa and Shape than for either Contour or Baseline configurations, $ts(11) > 7.66$, $ps < .0001$, all $d_z > 1.56$, all $BF_{10} > 1.66e+5$; and a main effect of experiment, $F(1, 22) = 18.32$, $p < .0001$, $\eta_p^2 = .45$, 90% CI [.18, .62], $BF_{10} = 86.52$, with higher thresholds in Experiment 2 ($M = 16.06$) than in Experiment 1 ($M = 8.80$). The interaction between configuration and experiment was also significant, $F(3, 66) = 5.43$, $p = .002$, $\eta_p^2 = .20$, 90% CI [.05, .31], $BF_{10} = 14.45$: there was no significant difference in thresholds between experiments for Baseline configurations, $t(11)= 1.91$, $p = .07$, $d = .78$, 95% CI [-.06, 1.61], $BF_{10} = 1.34$, but thresholds were overall higher in Experiment 2 than in Experiment 1 for Kanizsa, Shape, and Contour configurations, $ts(11) > 3.73$, $ps < .001$, all $d > 1.52$, all $BF_{10} > 26.95$.

[1] It should be noted that a Kanizsa figure is typically an example of modal completion – so that the term "Kanizsa", in a strict sense, would only be appropriate when describing the diamond stimulus as used in Experiment 1. However, for the sake of consistency (i.e., for providing a coherent terminology when describing our experimental manipulations), we nevertheless used comparable labels for our conditions throughout all experiments in this study.

Discussion

Experiment 2 presented amodal completion stimuli, where the illusory figure is perceived as being partially occluded. The results of Experiment 2 suggest that surface completion influences performance despite the occlusion, as amodal variants of Kanizsa and Shape configurations still exhibited a higher dot-localization sensitivity than corresponding Contour and Baseline stimuli. It should be noted in this regard that there was no significant difference in sensitivity when comparing the amodally completed contour and baseline configurations (the threshold for Contour was numerically even higher than for Baseline). This confirms that an illusory contour is not effectively completed across an occluder, but nevertheless an occluded region still modulates detection performance.

The occluded configurations in Experiment 2 led to an overall decreased sensitivity of dot localization for stimuli that induce an illusory region (Kanizsa, Shape, and Contour configurations), as compared to Experiment 1 with comparable modal-completion stimuli. However, no significant difference between the two experiments was found in the Baseline, suggesting that the performance reduction occurred because of the increased difficulty in processing the occluded object, but not because of a potential difference in perceptual complexity of the configurations that may have resulted from the addition of the outline circles.

To further substantiate that the non-significant differences between Kanizsa and Shape (d_z = .25), and between Contour and Baseline configurations (d_z = .27) were not due to a lack of statistical power, we conducted a second post-hoc power analysis, again setting power to 80% and the alpha level to .05 (two-tailed). In Experiment 1, the effect size of the smallest numerical contrast (i.e. between Kanizsa and Shape conditions) was 1.13, thus, revealing a large effect (cf. Cohen, 1988). The power analysis in fact showed that our current sample size would be sufficient to detect such an effect size. It is therefore unlikely that our non-significant effects can be attributed to a limitation in sample size. Moreover, an additional estimation of the Bayes factor for these non-significant differences revealed that both the comparisons between Kanizsa and Shape (BF_{10} = 0.40) and between Contour and Baseline (BF_{10} = 0.41) were clearly in favor of the null hypothesis.

Experiment 3

Experiment 2 provided clear evidence for a surface-based modulation of performance even though no illusory contour was visible in the presented (amodal) configurations. It could be argued, however, that amodal completion (i.e., the grouping of an object behind an occluder) is, in crucial ways, different from modal completion (e.g., in "standard" Kanizsa figures as tested in Experiment 1; see Murray, Foxe, Javitt, & Foxe, 2004). Experiment 3 was therefore performed to further investigate whether a performance modulation for surface-defined groupings (without a concurrent illusory contour) could also be demonstrated in cases of modal completion. To this end, configurations were presented with smoothed pacman inducers, which, in previous studies, have been shown to reveal surface completion, that is, affording selection based on a "salient region" (Shipley & Kellman, 1990; Stanley & Rubin, 2003), without a corresponding illusory contour (see Figure 5). If dot-localization sensitivity is modulated by the presence of a salient region alone, then surface filling-in and contour interpolation might be considered separate mechanisms that contribute to the completion of an illusory figure in both variants of modal and amodal completion.

Method

Experiment 3 was again basically identical to Experiments 1 and 2, with the following differences: 12 right-handed paid volunteers (5 men; mean age: 25.92 ± 5.57 years; normal or corrected-to-normal vision) participated in the experiment. There were two possible stimulus configurations: Kanizsa configurations, consisting of a salient, central object, were compared to Baseline configurations (i.e., stimulus arrangements that do not give rise to any emerging shape). In addition, these two types of configuration could be presented with two types of inducers, or edges ("sharp" and "smoothed"), resulting in four possible conditions: stimuli with "sharp" edges were essentially identical to the configurations presented in Experiment 1 (see Figure 5), whereas the sharp corners of the inducer shapes were eliminated in configurations with “smoothed” edges. In the smoothed variant of the Kanizsa configuration, this change of the inducers created the impression of an enclosed “salient region”, but without a crisp bounding contour (Shipley & Kellman, 1990; Stanley & Rubin, 2003; see Figure 5). Smoothed inducers were generated by manually tracing the outlines of the inducers to eliminate their sharp corners and then rotating each inducer by 10 degrees clockwise to eliminate the alignment of the straight parts of the edges. This procedure was similar to previous studies, which also used smoothed inducers (e.g., Stanley & Rubin, 2003).

Figure 5 about here

Results

Figure 6 presents the psychometric curves (top) and the corresponding mean discrimination thresholds (bottom) for the different conditions in Experiment 3 (upper and lower panels, respectively). A repeated-measures ANOVA with the factors configuration (Kanizsa, Baseline) and edge (sharp, smoothed) on the discrimination thresholds revealed a significant main effect of configuration, $F(1, 11) = 40.10$, $p < .0001$, $\eta_p^2 = .79$, 90% CI [.49, .86], $BF_{10} = 6.59e+4$: thresholds were lower for Kanizsa ($M = 8.35$) than for Baseline configurations ($M = 16.05$). The main effect of edge was not significant, $F(1, 11) = 3.91$, $p = .07$, $\eta_p^2 = .26$, 90% CI [0, .52], $BF_{10} = .54$, and there was also no interaction effect, $F(1, 11) = 1.47$, $p = .25$, $\eta_p^2 = .12$, 90% CI [0, .39], $BF_{10} = .68$. However, despite of the non-significant interaction, paired-t tests still revealed a significantly lower threshold for the Kanizsa configuration with sharp edges than that with smoothed edges, $t(11) = -2.74$, $p = .019$, $d_z = -.79$, 95% CI [-1.43, -.12], $BF_{10} = 3.49$, while there was no difference between the two edge types for Baseline configurations, $t(11) = -.30$, $p = .77$, $d_z = -.09$, 95% CI [-.65, .48], $BF_{10} = .30$.

Figure 6 about here

Discussion

Experiment 3 compared performance for Kanizsa and Baseline configurations with sharp and smoothed edges. In the Kanizsa configuration with smoothed edges, surface completion mechanisms typically render the impression of a closed, “salient region" that is perceived (even) without concurrent illusory contours (Stanley & Rubin, 2003). Accordingly, the results of Experiment 3 suggest that salient-region computations influence dot-localization performance even in the absence of illusory contours – as evidenced by a consistently higher sensitivity for Kanizsa as compared to Baseline configurations, independently of the type of edge (sharp or smoothed). Although the interaction was non-significant, there was still a significant difference between Kanizsa configurations with sharp and smoothed edges, consistent with Stanley and Rubin (2003) who used comparable stimuli and the same task. This pattern suggests that both surface information and contour processing contributed to the observed modulation of dot-localization sensitivity. For the Baseline condition, by contrast, there was no difference between configurations with smoothed and sharp edges, that is, the subtle physical difference between the two types of inducers alone did not impact the basic level of performance.

Together, Experiments 2 and 3 show that surface filling-in can facilitate the perception of modally and amodally completed configurations, over and above any contribution from the interpolation of illusory contours (e.g., as revealed in Experiment 1). This indicates that illusory contours and salient surfaces are computed by separate mechanisms that do not necessarily depend on each other.

Experiment 4

Across Experiments 1 to 3, an increased sensitivity was revealed for the Kanizsa figure as compared to configurations that do not induce a comparable illusory shape (e.g., the Baseline configuration). As outlined above, this difference can be explained by grouping mechanisms, according to which localization of the dot is more accurate when an illusory shape allows estimation of the precise position of the target dot in relation to the illusory figure. However, a potential alternative account may simply be that the advantage for the Kanizsa figure results from the shorter spatial distance between the edges of the two inward-facing pacmen in the Kanizsa figure, as compared to a somewhat larger distance between edges in the two outward-facing pacmen in the Baseline condition (see Figure 7A, left and middle panels for an illustration). Note that this latter account would attribute the observed differences in performance primarily to the distance between the edges of a configuration, rather than to the completion of an illusory figure. To exclude this potential confound, in Experiment 4, we equated the distances between the edges of two neighboring pacmen using rectangular variants of the Kanizsa figure and the Baseline configuration of Experiment 1.

Method

Experiment 4 was largely identical to Experiment 1, with the following differences: 12 right-handed paid volunteers (7 men; mean age: 25 ± 3.10 years; normal or corrected-to-normal vision) participated in the experiment. There were again four possible stimulus configurations in the experiment: The 'Smaller' Kanizsa and Baseline configurations were identical to the ones presented previously in Experiment 1. Two additional configurations presented larger, rectangular stimulus arrangements (the "Larger Kanizsa" and "Larger Baseline" configurations). For the larger Kanizsa configuration, the distance between the edges of the two pacmen on the side where the target dot appeared was the same as that of the original Baseline configuration in Experiment 1 (see Figure 7A, right and middle panels, respectively). The support ratio for the larger Kanizsa diamond was 0.29. The larger Baseline configuration was identical to the Baseline condition (also presenting no illusory object), but with the pacman inducers placed at same distances as for the larger Kanizsa stimulus configuration. These additional larger variants of the configurations permitted assessment of the effect of contour length on performance, while keeping the distance between the central fixation cross and the dot constant (for examples of the actual stimuli, see Figure 7B).

Figure 7 about here

Results

Figure 8 presents the psychometric curves for the different conditions and the corresponding mean discrimination thresholds in Experiment 4 (upper and lower panels, respectively). A repeated-measures ANOVA with the factors configuration (Kanizsa, Baseline) and size (smaller, larger) on the discrimination thresholds revealed a significant main effect of configuration, $F(1, 11) = 73.54$, $p < .0001$, $\eta_p^2 = .87$, 90% CI [.65, .92], $BF_{10} = 1.16e+7$, with lower thresholds for Kanizsa ($M = 9.07$) than for Baseline configurations ($M = 20.08$). In addition, the main effect of size was significant, $F(1, 11) = 5.77$, $p = .035$, $\eta_p^2 = .34$, 90% CI [.01, .58], $BF_{10} = 0.54$: thresholds were lower for the smaller ($M = 13.20$) than for larger configurations ($M = 15.95$) – though with the BF_{10} value providing no conclusive support for the alternative hypothesis. There was no interaction effect, $F(1, 11) = .18$, $p = .68$, $\eta_p^2 = .02$, 90% CI [0, .23], $BF_{10} = 0.37$. Theoretically of most importance, when equating the spatial distance between the edges of a configuration, there was still a significant difference between the smaller Baseline and the larger Kanizsa configuration, $t(11) = 4.78$, $p = .001$, $d_z = 1.38$, 95% CI [.56, 2.17], $BF_{10} = 64.75$: the threshold was lower for the larger Kanizsa ($M = 10.75$) than for the smaller Baseline configuration ($M = 19.01$).

Figure 8 about here

Discussion

Experiment 4 replicated the results of Experiment 1, in revealing a lower threshold for the larger Kanizsa configuration than for the Baseline even when controlling for the distance between the pacman inducers on the side on which the target dot appeared. This result indicates that the decreased discrimination threshold for the Kanizsa figure in Experiments 1 to 3 was not caused by variations in spatial distance between neighboring inducers in the various configurations. Rather, dot-localization sensitivity appears to be distinctly influenced by the completion of an illusory figure.

Moreover, Experiment 4 showed that sensitivity is reduced for the larger as compared to the smaller configurations, with this difference in size showing a particularly strong variation for the comparison between large and small Kanizsa figures ($t(11) = 4.94$, $p < .0001$, $d_z = 1.43$, 95% CI [.59, 2.23], $BF_{10} = 80.45$). This result suggests that the support ratio (i.e., the relation between the inducer disks and the illusory contour) determines the strength of the illusory figure and, as a result, perceptual sensitivity. This outcome is consistent with previous findings, which suggest that, although perceptual interpolation of subjective contours appears to be instantaneous and effortless, interpolation is constrained by spatial factors such as inducer size, inducer spacing, and overall size of the display. Larger inducers and smaller spacing between inducers have previously been shown to increase the subjective clarity of the interpolated contours (Watanabe & Oyama, 1988; Shipley & Kellman, 1992), suggesting that the perception of illusory contours is strongly tied to the support ratio (e.g., Banton & Levi, 1992; Kojo, Liinasuo, & Rovamo, 1993).

Experiment 5

Experiment 4 ruled out the possibility that the advantage for the Kanizsa figure is due to the shorter spatial distances between the edges of the pacmen inducers. However, an alternative explanation for our findings could be that the decreased sensitivity in the Baseline (relative to the Kanizsa) configuration is owing to the edge interruption by the inducer surface, which increases the difficulty of computing a boundary. That is, the pacman inducer with outward-oriented indent would impede the formation of a connecting line between the inducer edges in the Baseline, but not in the Kanizsa configuration, thus impeding the accuracy with which the inside-outside judgment can be made. To exclude this potential confound, in Experiment 5, we eliminated the visual interruption by using variants of inducer elements that simply consisted of collinearly arranged L-shaped line junctions (see examples in Figure 9). In addition, we controlled for spatial distance between the edges of the inducers in the different configurations (comparable to the procedure adopted in Experiment 4). Processing of object configurations is usually found to be equally efficient for shapes composed of circular inducers and line segments (e.g., in visual search; see Conci et al., 2007a; 2007b). We therefore expected that dot-localization performance would be modulated by the closure of the presented configurations (i.e., revealing a benefit for the Kanizsa configurations relative to the Baseline) regardless of the presence or absence of a visual interruption caused by the inducers (pacmen vs. line junctions).

Method

Experiment 5 was comparable to Experiment 4, with the following differences: 12

right-handed paid volunteers (6 men; mean age: 24.25 ± 2.56 years; normal or corrected-to-normal vision) participated in the experiment. There were again four possible stimulus configurations: First, the Kanizsa and Baseline configurations were presented with pacman inducers, similar to those in Experiment 4. Second, two additional configurations were presented that consisted of four L-shaped corner junctions, with the length of each line (1.1°; line thickness: 6 arc-min) being identical to the radius of the pacman inducers (see example stimuli with line inducers in Figure 9). The corner junctions were arranged in a diamond-like form, and either presented a closed shape (Kanizsa) or a corresponding open, cross-shaped (Baseline) configuration. The pacman and line inducers in the Baseline configurations were placed at the same distance as in the Kanizsa configurations (on the side where the dot probe appeared, see Figure 9) – resulting in rectangular baseline arrangements, which allowed performance to be assessed across the various configurations independently of variations of the task-critical boundary (see above, Experiment 4). All other details of the Kanizsa and Baseline configurations with line inducers were identical to the corresponding configurations with pacman inducers.

Figure 9 about here

Results

The psychometric curves and the corresponding mean discrimination thresholds for the different conditions are presented in Figure 10 (upper and lower panels, respectively). A repeated-measures ANOVA with the factors configuration (Kanizsa, Baseline) and inducer type (pacman, line) on the discrimination thresholds revealed a significant main effect of configuration, $F(1, 11) = 37.11$, $p < .0001$, $\eta_p^2 = .77$, 90% CI [.46, .85], $BF_{10} = 4.28e+4$, again with lower thresholds for Kanizsa ($M = 6.24$) than for Baseline configurations ($M = 12.11$). In addition, the configuration × inducer type interaction was significant, $F\ (1, 11) = 10.58$, $p = .008$, $\eta_p^2 = .49$, 90% CI [.1, .67], $BF_{10} = 6.12$, due to there being a significant difference between the pacman and line inducers for the Baseline configuration, $t(11) = 2.49$, $p = .03$, $d_z = .72$, 95% CI [.07, 1.35], BF_{10} =2.47, but no significant difference for the Kanizsa configuration, $t(11) = 1.59$, p =.14, $d_z = .46$, 95% CI [-.15, 1.05], BF_{10} =.77. Note, though, that a significant reduction of the threshold for Kanizsa relative to Baseline configurations was found for both types of inducer: pacman inducers: $t(11) = 6.42$, $p < .0001$, $d_z = 1.85$, 95% CI [.89, 2.79], BF_{10} =530.97; and line inducers: $t(11) = 2.95$, $p = .01$, $d_z = .85$, 95% CI [.17, 1.51], $BF_{10} = 4.75$]. Finally, there was no effect of inducer type, $F\,(1, 11) = .62$, $p = .45$, $\eta_p^2 = .05$, 90% CI [.00, .30], $BF_{10} = .33$.

As can be seen from Figure 10 (upper panel), the PSE appears to be shifted from the objective contour location, in particular for the Kanizsa configurations. We therefore tested the deviation from the objective location with a series of one-sample t-tests (2-tailed), as in Experiment 1. Both the PSE of the Kanizsa configurations with pacman and line inducers showed a significant deviation from the objective contour location, but interestingly in opposite directions: as in Experiment 1, the pacman version of the Kanizsa configuration exhibited a deviation towards inside locations ($M = -3.74$), $t(11) = -3.01$, $p = .012$, $d_z = -.87$, 95% CI [-1.52, -.19], $BF_{10} = 5.15$; by contrast, the line-inducer version of the Kanizsa configuration showed a deviation towards outside locations ($M = 5.43$), $t(11) = 2.38$, $p = .036$, $d_z = .69$, 95% CI [.04, 1.31], $BF_{10} = 2.12$. [All Baseline conditions, $ts(11) < 1.9$, ps > .08, all $d_z < .55$, all $BF_{10} < 1.1$.]

Figure 10 about here

Discussion

Experiment 5 revealed a reduced dot-localization sensitivity for Baseline than for Kanizsa configurations, which was largely independent of inducer type. This shows that the observed performance difference can be attributed to the completion of an illusory figure, which enhances perceptual sensitivity irrespective of any visual edge interruption produced by the pacman inducer surface (in the Baseline condition). However, despite a clear effect of grouping upon performance, the interruption nevertheless modulated the efficiency of dot localization in the Baseline configurations. In particular, thresholds were reduced in Baseline configurations with (non-interrupted) line inducers as compared to (interrupted) pacman inducers –showing that without an emergent figure, the computation of a task-relevant object boundary depends on the efficiency with which inducers can be integrated to form a connecting line. Of note, this finding is essentially the same as the reduction of sensitivity in Experiment 2 relative to Experiment 1, where the addition of circular rings to the inducers (in Experiment 2) resulted in an overall performance decrease due to the interruption of the connection between neighboring pacman inducers.

In addition, Experiment 5 revealed another interesting result, namely: the PSE for Kanizsa configurations with pacman and line-inducers deviated from the objective contour location in opposing directions. In particular, participants tended to perceive the boundary of the Kanizsa configuration with pacman inducers as being curved towards the inside (as in Experiment 1), and with line inducers as being curved towards the outside. Comparable findings were reported in previous studies with pacman (Guttman & Kellman, 2004; Gintner et al., 2016) and line (Gegenfurtner, Brown, & Rieger, 1997; Conci et al., 2007b) inducers. With the line inducers, this 'outside' bias might arise because observers perceive an illusory square that appears to be completed in front of the L-inducer, diamond-shaped grouping.

General Discussion

In the current study, we probed the sensitivity of illusory figure perception by means of a dot-localization task, and established separable influences of contour- and surface-related processing by gradually manipulating various aspects of grouping in the stimulus configurations. Sensitivity was estimated from the discrimination threshold of the psychometric functions of dot-localization performance: the lower the discrimination threshold (i.e., the steeper the slope), the higher the sensitivity. Experiment 1 showed that sensitivity was modulated by both the amount of surface and contour information present in a given configuration, with the highest sensitivity for (complete) Kanizsa figures, followed by Shape and Contour configurations, and the lowest sensitivity for the Baseline configuration. This pattern indicates that both surface filling-in and contour interpolation contribute to the formation of the illusory figure. In Experiment 2, the same experimental logic was applied to occluded object configurations. For the amodally completed stimuli, the sensitivity was overall reduced (i.e., in Kanizsa, Shape, and Contour stimuli). In addition, while the difference between Contour and Baseline stimuli disappeared, Kanizsa and Shape configurations still afforded higher sensitivity than Contour and Baseline configurations – suggesting that the formation of an illusory surface continued to facilitate performance even when contour interpolation processes were not available (due to object occlusion). Next, in Experiment 3, separable processing of contour and surface information was further investigated by presenting modal completion configurations with smoothed inducers, which group to form a coherent surface region but without concurrent illusory contours. The results from these "salient-region" stimuli again showed an increased perceptual sensitivity relative to the Baseline configurations. Thus, together, the results of Experiments 2 and 3 consistently show that contour and surface processing can be dissociated to some extent in the completion of an illusory figure, that is, they provide separable influences on performance. Finally, Experiments 4 and 5 were performed as control experiments to confirm that the performance benefit for Kanizsa figures was due to the completion of an illusory figure, rather than being attributable to subtle variations in distance between the pacman elements in the configurations presented (Experiment 4), or due to visual (edge) interruption which interferes with the computation of a boundary in the Baseline configuration (Experiment 5).

Taken together, our results support the view that the completion of illusory contours and surfaces provide essential contributions to the formation of illusory Kanizsa figures, as both contribute to dot-localization performance (see Experiments 1–3). This supports common explanations of the underlying mechanisms of modal completion (see Pessoa et al., 1998, for a review), and is consistent with previous observations that both processes of surface and contour grouping are available preattentively (Conci et al., 2009; see also Mattingley, Davis, & Driver, 1997). At the same time, however, the results are, to some extent, inconsistent with findings from visual search, which indicated that only the surface but not the surrounding contours determine the efficiency of detecting Kanizsa figure targets among distractors (Conci et al., 2007a). This difference in results is likely attributable to differential task requirements, as the role of contour interpolation might be underestimated in a visual search task where attention is to be focused on a relatively broad representation of the Kanizsa target shape (see also Stanley & Rubin, 2003). In this view, the allocation of attention appears to be determined by the specifics of a given task: a relatively broad estimation of a salient region might suffice to detect an illusory square in visual search, whereas the dot-localization task engenders more precise discrimination processes that require the engagement of both contour and surface completion to render a more precise shape representation.

In general, mechanisms of figure-ground segregation are thought to be involved in integrating inducer information so as to represent an illusory surface as lying in front of the pacman inducer disks (Kogo et al., 2010; Kogo & Wagemans, 2013). Note that we found that surface construction processes yield a performance benefit even when illusory contours are not perceived due to occlusion (Experiment 2), or as a result of smoothed pacmen inducers (Experiment 3). Although it is not possible to perceive explicit, definitive contours with these variants of the illusory objects, observers nevertheless appeared to perceive the continuation of the surface behind the pacmen, or a salient region that was formed in the absence of sharp boundaries, and, as a result, detected the illusory shape, leading to an increase of their perceptual sensitivity (see also Van Lier, 1999).

To explain how Kanizsa figures are completed, it has been proposed that processing of the illusory figure is accomplished by a feedforward, serial mechanism (Grosof, Shapley, & Hawken, 1993; Ffytche & Zeki, 1996), during the operation of which surface filling-in is achieved only after the interpolation of the respective illusory contours. In this view, the boundaries of an object are computed first and the surface is generated only afterwards. However, the present results provide strong evidence that illusory contours and the corresponding surfaces are computed by separate mechanisms that are not necessarily dependent on each other (see also Grossberg & Mingolla, 1985; Dresp & Bonnet, 1991; Dresp, Lorenceau, & Bonnet, 1990; Rogers-Ramachandran & Ramachandran, 1998). In fact, illusory surfaces can be generated without an exact specification of the illusory contours that demarcate the object boundaries (Experiments 2 and 3; see also Stanley & Rubin, 2003). This pattern, of separable processing of contours and surfaces, is difficult to explain by a serial, feedforward process. Arguably, a better explanation is provided by recurrent models of completion, on which completion of illusory figures results from a series of feedforward and feedback loops, with processing operating in parallel at various levels in the visual hierarchy (Lamme & Roelfsema, 2000; Roelfsma, Lamme, Spekreijse, & Bosch, 2002; Kogo et al., 2010; Kogo & Wagemans, 2013). On such a recurrent-network account, different object components may be specified with relative independence of each other. For instance, parallel, feedforward processing may initially extract contours and surfaces independently of each other via separate mechanisms. The combination of their outputs is then accomplished by a recurrent feedback process that combines the estimated surface with the associated contours to form a coherent whole.

In line with this account, Stanley and Rubin (2003) reported fMRI evidence suggesting that the visual system first detects the "salient regions" of an object at higher cortical levels (e.g., in the LOC; Seghier & Vuilleumier, 2006), and this crude region estimation is then complemented by contour-sensitive processes in lower cortical regions (V1/V2 regions) through a top-down feedback loop that, in turn, refines the perception of the surface and determines its precise edges. Moreover, Shpaner, Molholm, Forde, and Foxe (2013) reported evidence to suggest that the flow of information via feedforward and feedback connections across various levels in the visual hierarchy facilitates the perception of the whole illusory figure. In general agreement with these accounts, the current findings show that completion of illusory contours is supported by complementary processes of surface filling-in, yielding higher sensitivity for Kanizsa and Shape compared to Contour configurations (see Experiment 1). This might be the result of a refined object representation that first extracts the respective surface and contour information, with subsequent, recurrent feedback iterations combining these sources of information to represent the whole illusory figure.

Conclusions

Object completion – as exemplified in the Kanizsa figure – is a fundamental operation of human vision and observed in many instances, with the representation of a coherent whole determining all subsequent higher-order cognitive and emotional processing (see, e.g., Erle, Reber, & Topolinski, 2017). Thus, identification of the mechanisms underlying object completion (in Kanizsa figures) is essential for a complete understanding of human vision. The current study established an approach for effectively investigating these mechanisms by examining illusory figure sensitivity using a dot-localization task while comparing and contrasting the relative impact of the available contour and surface information. Collectively, the results obtained provide further support for a multi-stage model of object processing. Illusory contour and surface completions are both closely related to fundamental mechanisms of the visual system by which illusory figures are grouped, interacting through a series of feedforward and feedback loops.

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Open Practices

All data and materials have been made publicly available via the open science framework and can be accessed at https://osf.io/3ydju/.

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Figures and Table

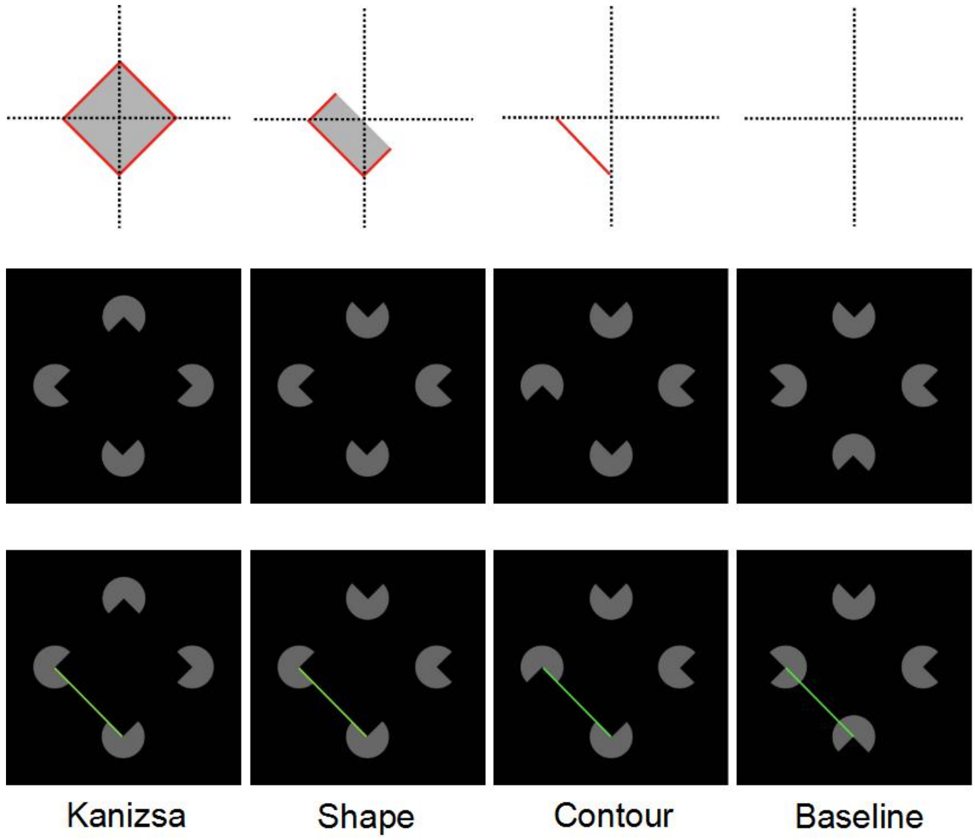


Figure 1. Examples of the modal completion stimuli used in Experiment 1. An example of each possible configuration (Kanizsa, Shape, Contour, Baseline) is depicted in the middle panels. In the examples, partial groupings in the Shape and Contour stimuli are induced in the bottom-left quadrants of a given configuration. The top panels illustrate the corresponding emergent grouping, displaying the respective surface (gray) and contour (red) completion. In addition, the bottom panels illustrate the presumed boundary of the inner region for a given configuration (green line) when the dot appeared on the left side. Note that the green line was not shown in the actual experiment, but only serves to illustrate the respective borders. See text for further details.

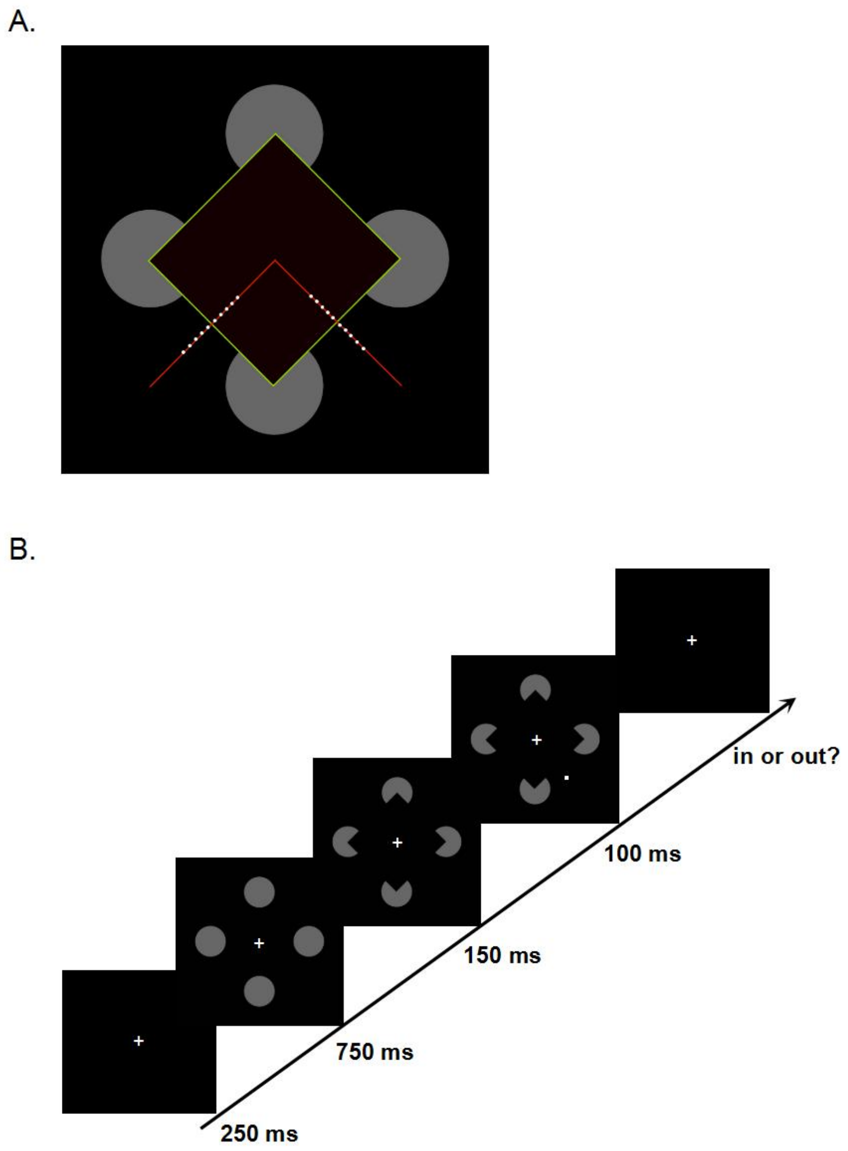
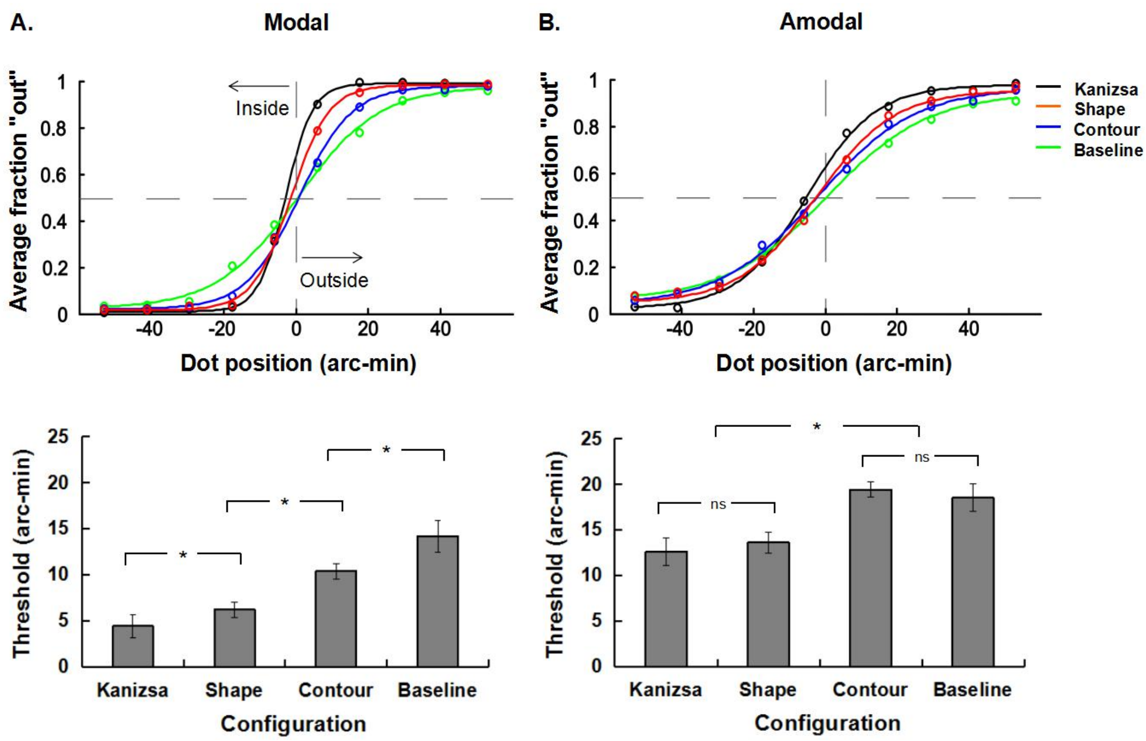


Figure 2. (A) Illustration of possible dot locations in the experiments. The dot probe appeared at one of ten equidistant locations along the midline (red) perpendicular to the bottom left or right border (green) of the illusory figure. Note that the red and green lines were not shown in the actual experiment; they only serve to illustrate the stimulus layout. (B) Example trial sequence in the dot-localization task. Subsequent to a pre-cue display (750 ms), a configuration display (either Kanizsa, Shape, Contour, or Baseline) was briefly presented (150 ms), after which a dot probe was added and presented for another 100 ms. In the example, the dot is presented near the bottom right boundary of the enclosed region. Observers were instructed to report whether the dot appeared inside or outside the enclosed illusory region. In the example, the correct response would be 'out'.



<u>Figure 3</u>. Upper panel: Psychometric curves in the dot-localization task, across observer means, in Experiment 1 (A) and Experiment 2 (B). In the graphs shown, the fraction of 'out' responses is plotted against dot position, for the Kanizsa, Shape, Contour, and Baseline conditions in the modal (A) and amodal (B) configurations. Steeper slopes indicate perception of a sharper illusory figure. Note that positive values on the x-axis indicate "outside" dot-locations and negative values "inside" locations. Lower panel: Corresponding mean discrimination thresholds in the Kanizsa, Shape, Contour, and Baseline conditions in Experiment 1 (A) and Experiment 2 (B). Error bars denote 95% within-subject confidence intervals. *$p < .05$, Bonferroni corrected.

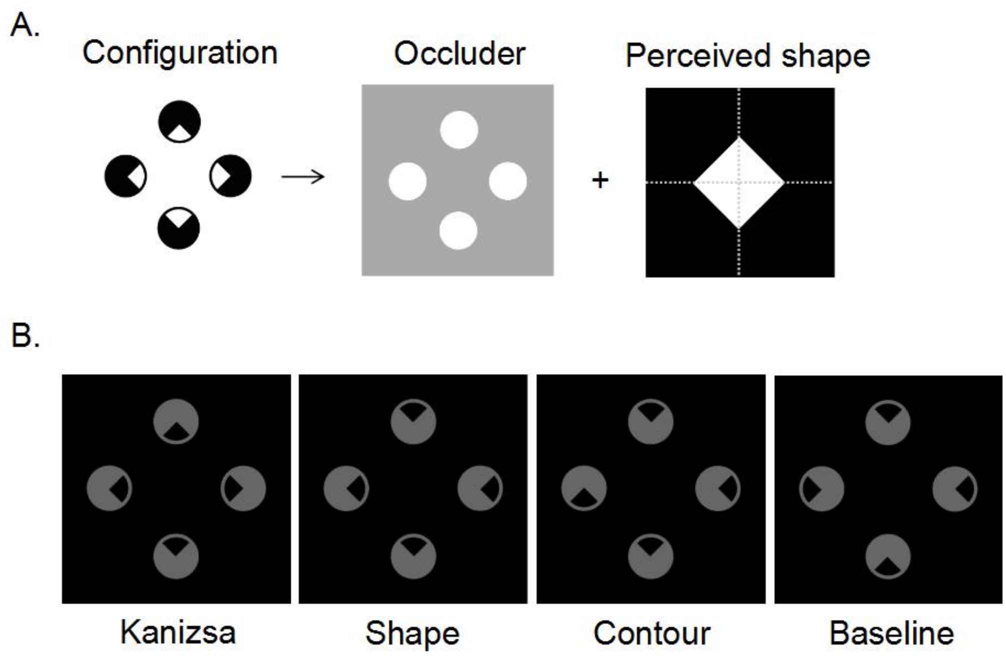


Figure 4. (A) An example configuration that leads to amodal completion. In the configuration, a diamond shape is perceived as lying behind an occluding surface. (B) Examples of the amodal completion stimuli used in Experiment 2. Partial groupings in the Shape and Contour stimuli are induced in the bottom-left quadrants of a given configuration.

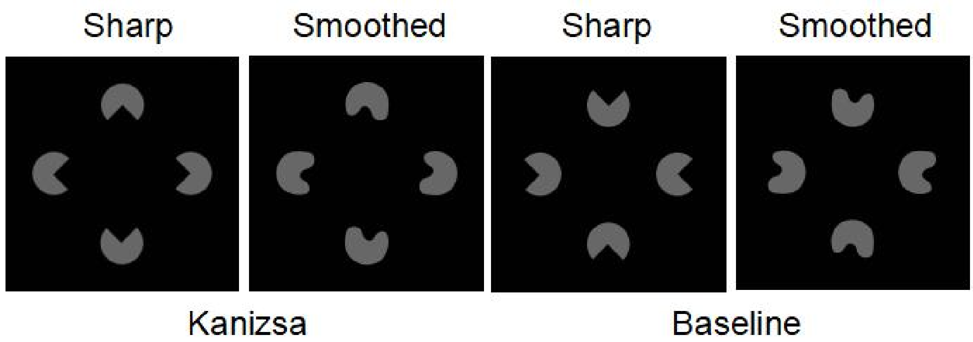


Figure 5. Example stimuli used in Experiment 3. The Kanizsa and Baseline configurations with sharp edges are the same as in Experiment 1. In the Kanizsa configuration with smoothed edges, the arrangement of the inducing elements creates an impression of an enclosed “salient” region, but this region is not bounded by crisp illusory contours.

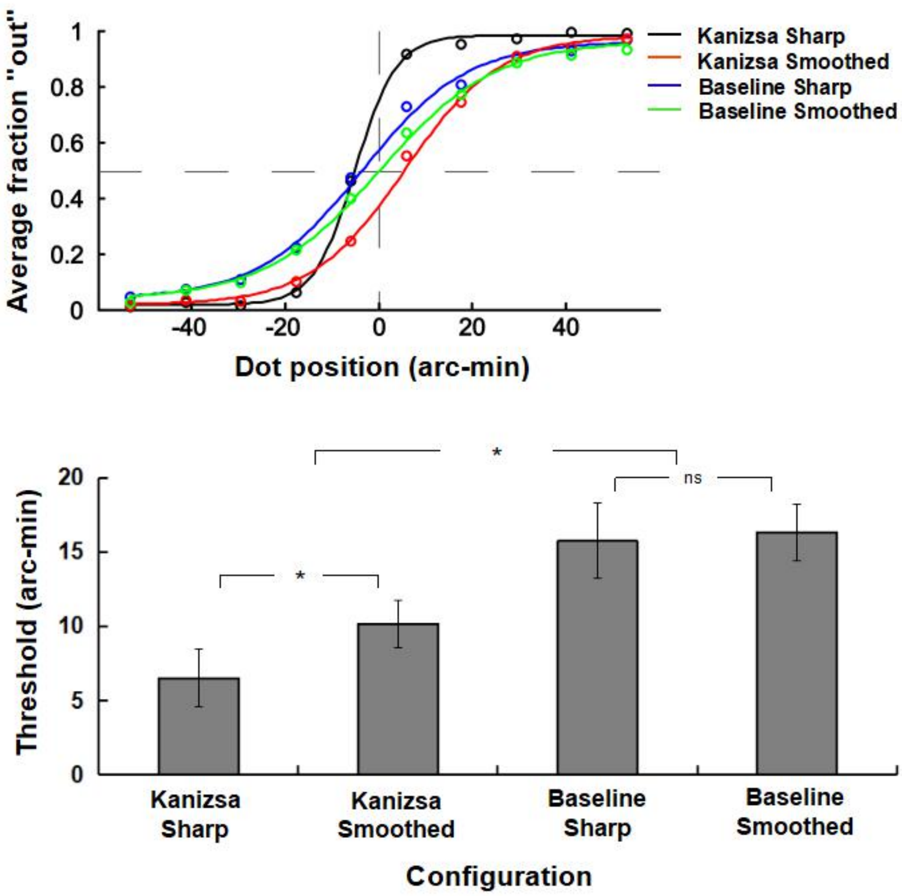


Figure 6. Upper panel: Psychometric curves in the dot-localization task, across observer means, in Experiment 3. The fraction of 'out' responses is plotted against dot position, for the Kanizsa and Baseline configurations with sharp or smoothed edges. Lower panel: Mean discrimination thresholds in the Kanizsa and Baseline configurations with sharp/smoothed edges in Experiment 3. Error bars denote 95% within-subject confidence intervals. *$p < .05$, Bonferroni corrected.

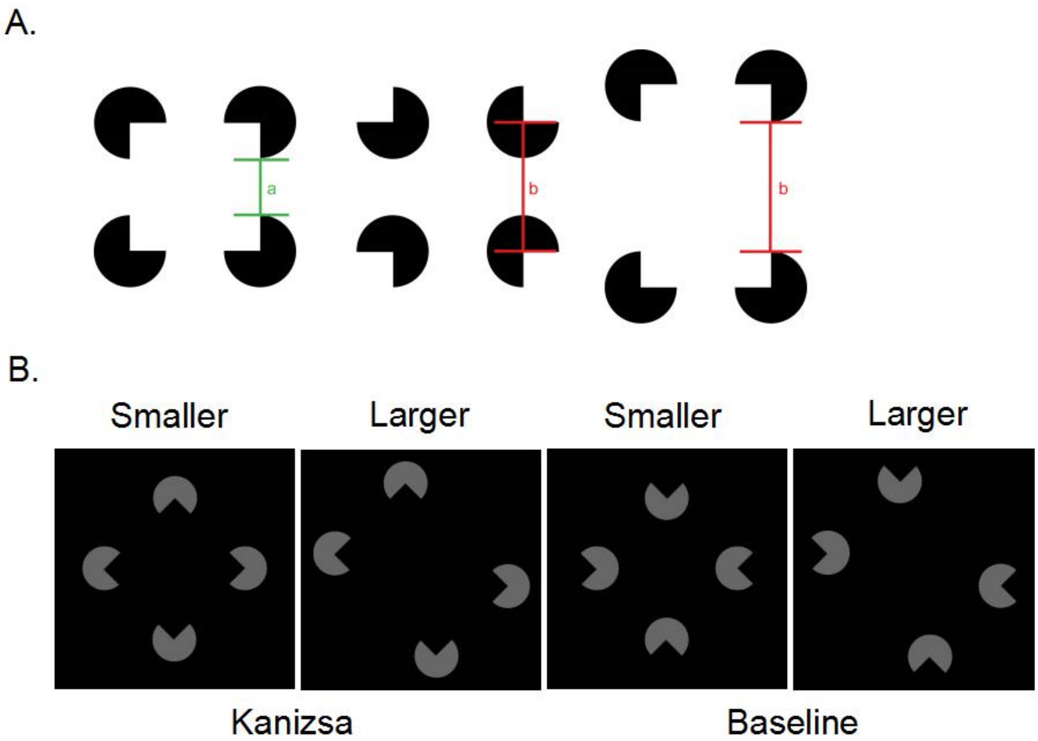


Figure 7. (A) Variations in spatial distance across the edges of the (smaller) Kanizsa (left panel, a) and (smaller) Baseline (middle panel, b) configurations. In the larger Kanizsa configuration (right panel), the edge length is comparable to the smaller Baseline configuration. (B) Example stimuli in Experiment 4. The smaller Kanizsa and Baseline configurations were the same as in Experiment 1.

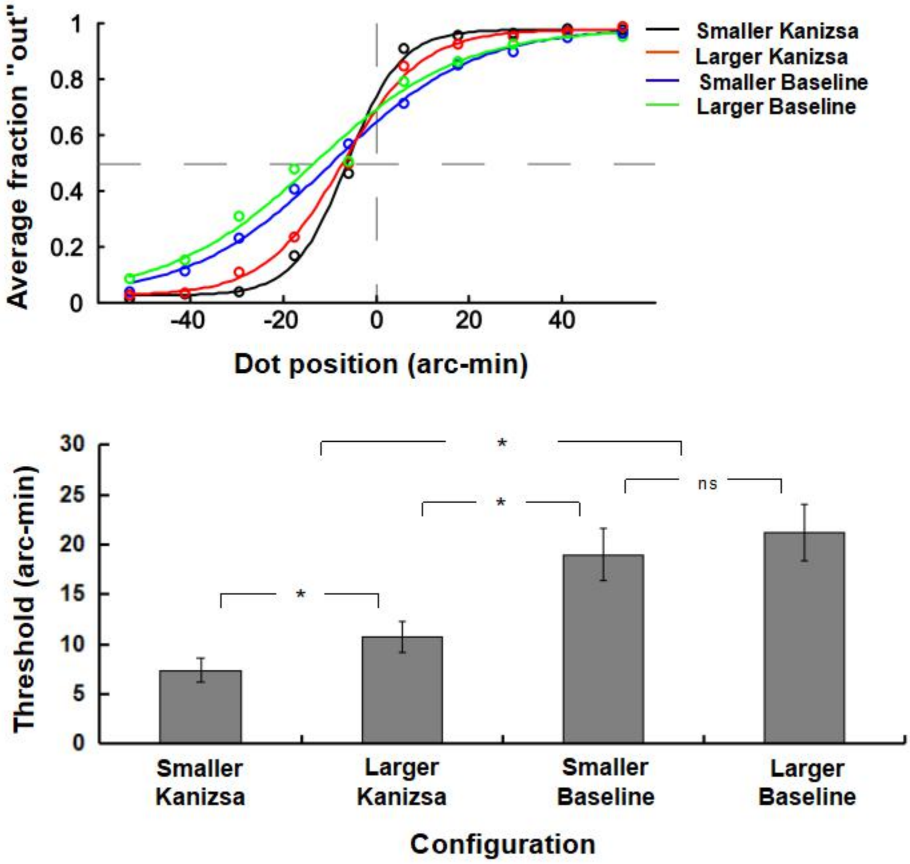


Figure 8. Upper panel: Psychometric curves in the dot-localization task, across observer means, in Experiment 4. The fraction of ‘out’ responses is plotted against dot position, for the smaller Kanizsa, larger Kanizsa, smaller Baseline, and larger Baseline conditions. Lower panel: Mean discrimination thresholds in the smaller Kanizsa, larger Kanizsa, smaller Baseline, and larger Baseline conditions in Experiment 4. Error bars denote 95% within-subject confidence intervals. *$p < .05$, Bonferroni corrected.

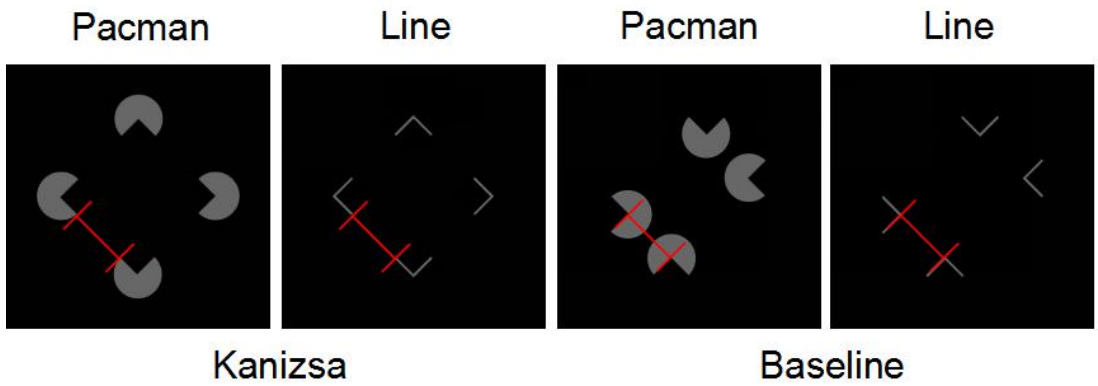


Figure 9. Example stimuli in Experiment 5, with variations of the inducer type in Kanizsa and Baseline configurations. In the Baseline configurations with pacman and line inducers, the edge length on the side where the dot appears is comparable to that in the respective Kanizsa configurations (see red lines; the line did not appear in the actual experiment). The Kanizsa figure was the same as in Experiment 1.

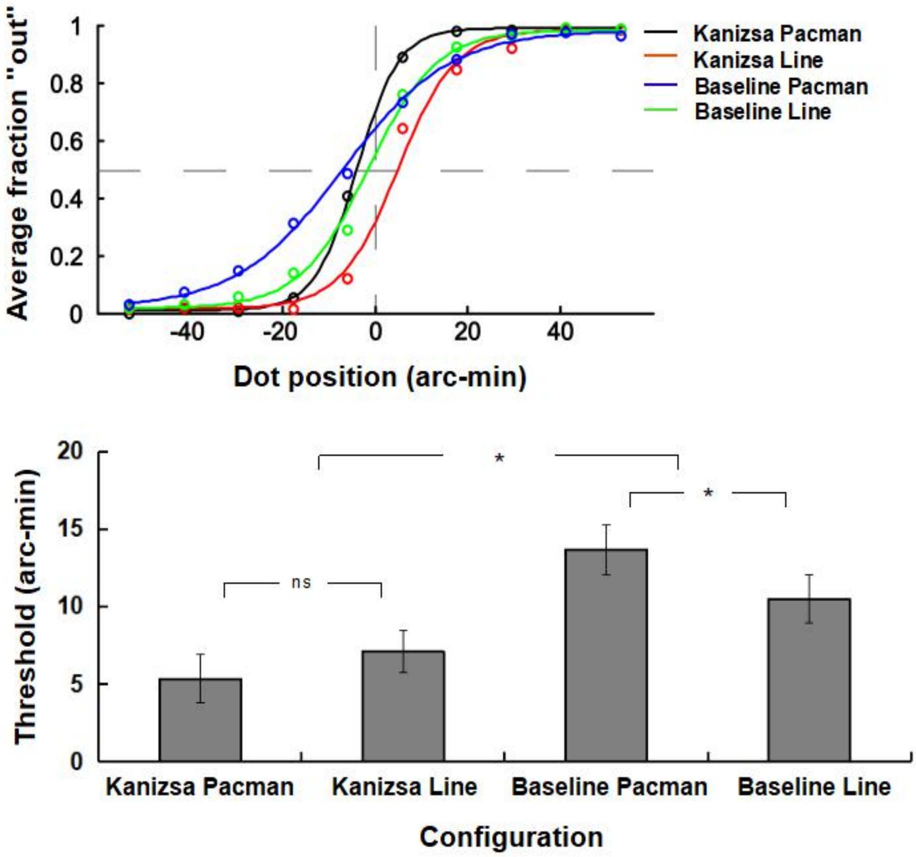


Figure 10. Upper panel: Psychometric curves in the dot-localization task, across observer means, in Experiment 5. The fraction of ‘out’ responses is plotted against dot position, for the Kanizsa and Baseline configurations, separately for pacman and line inducers. Lower panel: Mean discrimination thresholds in the Kanizsa and Baseline configurations with pacman/line inducers in Experiment 5. Error bars denote 95% within-subject confidence intervals. *$p < .05$, Bonferroni corrected.