
Interpolation processes in the perception of real and illusory contours

Karl R Gegenfurtner, Joel E Brown, Jochem Rieger

Max-Planck-Institut für biologische Kybernetik, Spemannstrasse 38, 72076 Tübingen, Germany;

e-mail: karl@mpik-tueb.mpg.de

Received 4 February 1997, in revised form 1 August 1997

Abstract. The spatial and temporal characteristics of mechanisms that bridge gaps between line segments were determined. The presentation time that was necessary for localisation and identification of a triangular shape made up of pacmen, pacmen with lines, lines, line segments (corners), or pacmen with circles (amodal completion) was measured. The triangle was embedded in a field of distractors made up of the same components but at random orientations. Subjects had to indicate whether the triangle was on the left or on the right of the display (localisation) and whether it was pointing upward or downward (identification). Poststimulus masks consisted of pinwheels for the pacmen stimuli or wheels defined by lines. Stimuli were presented on a grey background and defined by luminance or isoluminant contrast. Thresholds were fastest when the triangle was defined by real contours, as for the pacmen with lines (105 ms) and the lines only (92 ms), slightly slower for corners (118 ms) and pacmen (136 ms), and much slower for the amodally completed pacmen (285 ms). For all inducer types localisation was about 20 ms faster than identification. In a second experiment the relative length of the gap between inducers was varied. Thresholds increased as a function of gap length, indicating that the gaps between the inducers need to be interpolated. There was no significant difference in the speed of this interpolation process between the pacman stimuli and the line-segment stimuli. About 40 ms were required to interpolate 1 deg of visual angle, corresponding to about one third of the distance between inducers. In a third experiment, it was found that processing of isoluminant stimuli was as fast as for low-contrast luminance stimuli, when targets were defined by real contours (lines), but much slower for illusory contours (pacmen). The conclusion is that the time necessary to interpolate a contour depends greatly on the spatial configuration of the stimulus. Since interpolation is faster for the line-segment stimuli, which do not elicit the percept of an illusory contour, the interpolation process seems to be independent of the formation of illusory contours.

1 Introduction

The perception of illusory contours has been extensively studied in the past (for an overview see Petry and Meyer 1987). However, the emphasis has been mostly on the qualitative aspects of such displays, since the perception of such illusory figures could not be explained by contrast-energy-based models of visual perception. More recent physiological experiments (von der Heydt et al 1984; von der Heydt and Peterhans 1989; Peterhans and von der Heydt 1989) showed that even at a rather early level of the visual system, extrastriate cortical area V2 of macaque monkeys, there are mechanisms that potentially underlie the perception of such figures. Von der Heydt et al (1984) found cells that responded well to stimuli that can elicit the perception of illusory contours, even though the inducing elements were located entirely outside of the classical receptive field of the cells. These experiments gave clear evidence that the gaps between the inducing elements can be bridged by such early mechanisms. Since then a number of psychophysical studies have also found evidence for an early, low-level processing of illusory contours (Shapley and Gordon 1987; Dresch and Bonnet 1991, 1993, 1995; Dresch 1993; Kojo et al 1993; Ringach and Shapley 1996; for a review, see Spillmann and Dresch 1995). Further physiological experiments (Redies et al 1986; Groszof et al 1993; Hirsch et al 1995) have also supported the hypothesis of an early-processing mechanism for the perception of illusory contours.

Even though the physiological experiments show strong neuronal responses to stimuli eliciting the percept of illusory contours, it is not clear whether the response magnitude of the cells correlates with the perceived strength of the illusory contours. Alternatively, the neuronal responses could be the substrate of the interpolation process that presumably takes place between the inducers. In our experiments we measured the temporal characteristics of this interpolation process. In experiment 1 we measured the dependence of the interpolation process on the spatial configuration of the inducing elements. We compared Kanizsa-triangle stimuli, which lead to a strong percept of illusory contours, with stimuli consisting of line segments, for which no illusory contours are perceived.⁽¹⁾ By measuring the speed of the interpolation process for these two types of stimuli in experiment 2, we could test whether the difference is in latency only or whether two mechanisms with different speeds of interpolation are involved. Last, since it has been argued that the percept of illusory figures is impaired under conditions of isoluminance (Gregory 1977; Ejima and Takahashi 1988; Livingstone and Hubel 1988; Li and Guo 1995), we have also looked at the interpolation process under such conditions.

Our results show that the time required to bridge the gap between inducing elements is the same for illusory contours and for line segments, which do not elicit the percept of illusory contours. This implies that the process responsible for grouping the target elements into a perceptual organisation, presumably a contour-continuation process, is independent of the process responsible for the formation of illusory contours.

2 Experiment 1: Spatial configuration

2.1 Methods

2.1.1 *Equipment.* The experiments were run on a Silicon Graphics Indigo II workstation. The monitor was 38.5 cm wide and 28.5 cm high. Subjects were seated at a viewing distance of 130 cm and viewed the display binocularly and through natural pupils. The monitor was run at a refresh rate of 72 Hz, allowing stimulus exposure durations which were multiples of 13.88 ms. Lookup tables for each of the three monitor phosphors were used to linearise the voltage versus luminosity function of the monitor.

2.1.2 *Subjects.* Fifteen subjects participated in experiment 1. Some of them were highly trained psychophysical observers, including one of the authors (JR). All of them had participated in at least five sessions of similar experiments before data collection for this experiment started. All subjects had normal or corrected-to-normal visual acuity.

2.1.3 *Stimuli.* The basic stimulus can be seen in figure 1a. For better reproduction the figure-ground contrast was reversed in figure 1 and all subsequent figures, which show black stimuli on a white background. In the actual experiments white stimuli were presented on a neutral grey background. Each stimulus display consisted of rows with six or seven inducing elements. These inducing elements were spaced evenly in a hexagonal grid with the centres 183 pixels (2.5 deg) apart. Typical stimulus screens are shown in figures 1a–1e. The inducing elements were as follows.

(a) Pacmen⁽²⁾: they consisted of filled circles 60 pixels (50 min arc) in radius, with a 60° sector missing.

(b) Pacmen with lines: like type (a) above, but here lines extended from the 'mouth' of the pacmen. The length of the lines was chosen so that two aligned lines connected across the gap. The lines were 2 pixels wide (1.65 min arc).

(c) Long lines: each figure was the corner of an equilateral triangle with lines 2 pixels wide, same as for (b), but without the pacmen.

⁽¹⁾ When looking at figure 1d, some observers might get the impression of an inverted illusory triangle defined by the gaps between the corners. However, at the short presentation times we used, this illusory percept is not visible.

⁽²⁾ The basic elements forming a Kanizsa triangle.

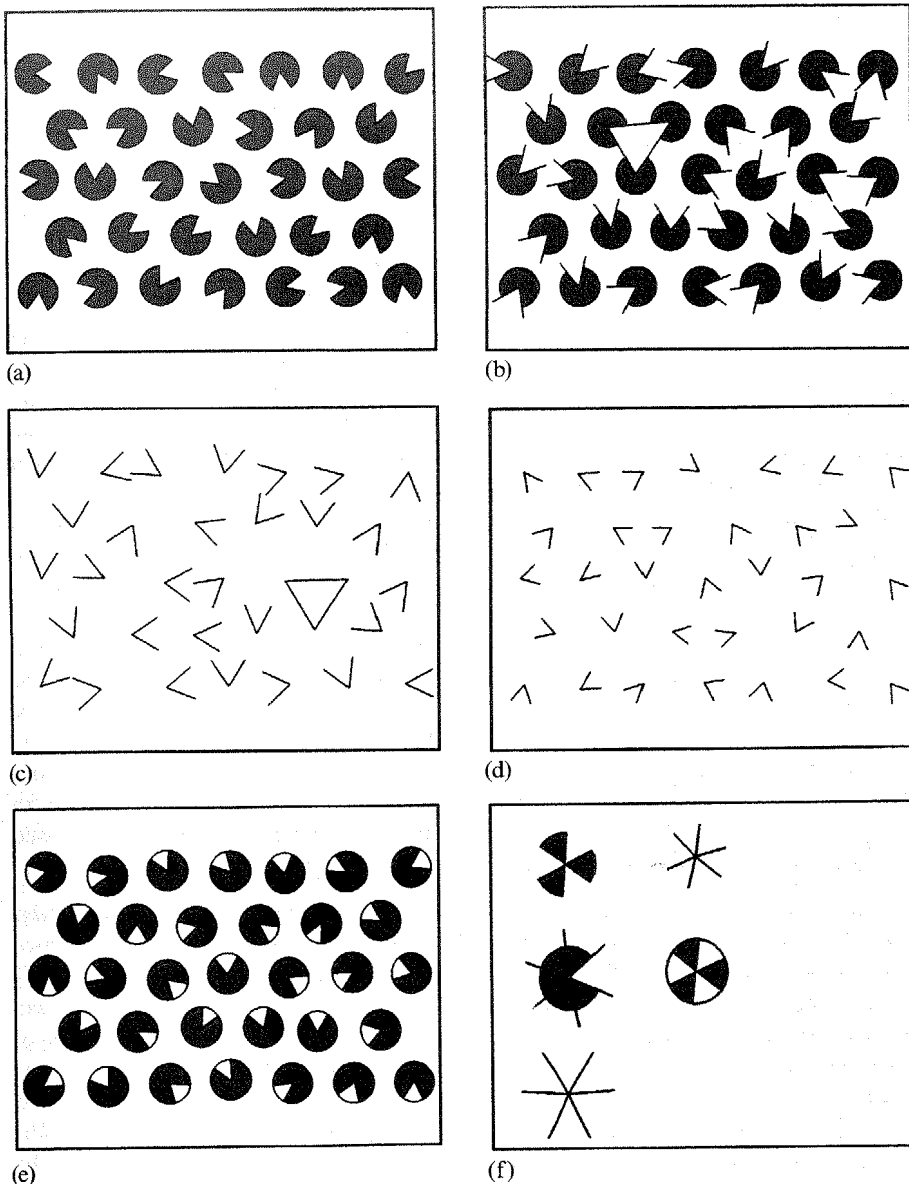


Figure 1. Stimuli used in these experiments. For illustration purposes stimuli are presented as black on a white background. However, in the experiment they were white on a grey background. The target was an equilateral triangle embedded in a field of randomly oriented stimulus elements. The triangle was displayed either to the left or to the right of the vertical midline, and was pointing upward or downward. The triangle was defined by (a) pacmen, (b) pacmen with connecting lines, (c) connected lines, (d) corners only, or (e) pacmen surrounded by a circle. Following the display of the stimulus pattern, a mask was presented spatially coincident with the stimulus. (f) Mask types, corresponding to the patterns shown in (a) through (e): left column, top to bottom—pinwheel mask, pacmen with wheel, wheel with long lines; right column, top to bottom—wheel with short lines, pinwheel with circle.

(d) Corners: this type of stimulus was like (c) above, but the length of the lines was equal to the length of the side of the 'mouth' of the pacmen as in stimulus type (a).

(e) Pacmen with circles: this type was like type (a) with a circle 2 pixels wide around the pacmen closing the missing sector.

The centre of each figure was randomly jittered by up to 10 pixels both horizontally and vertically. The opening angle of each corner or pacman was randomly jittered by up to 10° (to yield angles of 50° to 70°). Additionally, the starting points of these angles were random for each figure, except for the three inducers which made up the target.

To produce the targets, three adjacent figures forming an (almost) equilateral triangle on the grid were selected. The three figures were aligned so that the inducing elements formed a triangle. For the pacmen inducers, type (a), this resulted in the perception of an illusory triangle (Kanizsa 1979). For the lines (b, c), an outline triangle resulted. For the pacmen with circles (e), the resulting triangular shape is less visible and can be seen as lying behind the occluding pacmen. This is called amodal completion, after Kanizsa (1979). The position of the target was constrained to lie away from the centre and edges of the screen (figure 1a). It occurred with equal probability on the left or right side of the display. The orientation of the triangle was also randomised, so that the triangle pointed upward or downward with equal probability. Stimuli were followed by a mask. In experiment 1 white stimuli (60 cd m^{-2}) were presented on a uniform grey background with a luminance of 30 cd m^{-2} .

Note that without the jittering two of the inducers would always be horizontally oriented, and the task could potentially be performed just by searching for horizontal orientations. With the jitter, information from all three inducers needs to be combined to perform the task.

At the beginning of each trial, a central fixation spot was displayed for 1 s. It was followed by the target screen (ie figure 1a), which was displayed at variable durations between 13.88 and 1000 ms. After the target screen a mask screen was shown for 1 s, which was followed by a uniform grey screen. The mask screen contained the same number of figure elements as the target in exactly the same positions. These figure elements were chosen to effectively mask each inducer element. The figure elements of the masking stimuli are illustrated in figure 1f. In particular, pinwheel masks were used for pacmen stimuli, and a wheel of six evenly spaced line segments for the line stimuli.

2.1.4 Procedure. The objective of the experiments was to determine the target-presentation time required for observers to reliably (i) localise the triangle by indicating on which side of the screen (left or right of midline) the target figure appeared, and (ii) identify the orientation of the triangle by indicating whether it was pointing upward or downward. On each trial, the observer made both decisions by pressing the left arrow or right arrow key on the keyboard for localisation and the up arrow or down arrow key for identification. These keys were arranged on the keypad to lie on the sides of a square. After the subject pressed both buttons, the next trial started with a delay of 1 s. The subject's task was only to indicate the position and orientation of the shape. We did not require any subjective reports, for example about the presence of illusory contours.

The method of constant stimuli was used. In each block of trials a single type of inducer was used with five to seven constant presentation times ranging from 13.88 ms to 1000 ms. Each stimulus was presented in random order fifteen to twenty-five times during each block. Several blocks of trials, one for each inducer type in the experiment, were run in each experimental session. Each subject was tested in twenty to one hundred trials for each inducer type at each presentation time.

The percentage of correct responses at each presentation time was used to calculate thresholds for localisation and identification for the triangular shapes defined by the different inducer types. Cumulative Gaussian functions were fitted to the proportion of correct responses, as illustrated in figure 2. Guessing probability was 50% in the experiment and the lower asymptote of the psychometric function was therefore fixed at that value. Threshold was defined as the presentation duration at which the psychometric function predicted a performance of 75% correct. For all functions we obtained

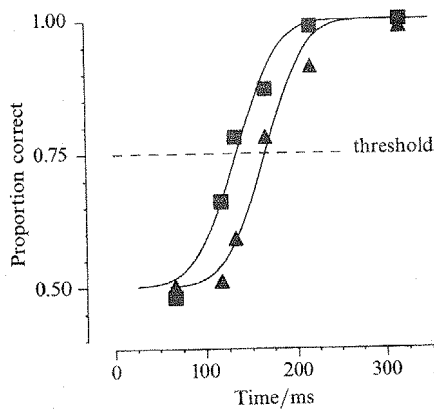


Figure 2. Example psychometric functions used to extract the thresholds for localisation and identification. Data are shown for observer TR for the localisation (squares) and identification (triangles) of a Kanizsa triangle embedded in a field of pacmen. Four to six sessions with one hundred trials for each inducer type were run for each observer. Exposure times were chosen after the initial sessions around the threshold range. A cumulative Gaussian curve was fitted to the proportion of correct responses and the mean of the Gaussian was defined as the threshold where subjects could reliably perform the task.

an excellent fit for the range of presentation times close to threshold, since that was the only parameter extracted from each data set. If necessary, presentation times were adjusted between sessions to match each subject's individual threshold range.

2.2 Results

2.2.1 Different inducer types. Figure 3 shows the average performance of all fifteen observers. The five different inducer elements are indicated on the *x*-axis. Thresholds for correctly identifying the triangular shape (left side of each pair of columns) and for localising it (right side) are plotted on the *y*-axis. An analysis of variance revealed significant effects of inducer type ($p < 0.01$), task ($p < 0.01$), and their interaction ($p > 0.01$). On average, subjects were 23 ms faster in localising the triangular shapes than in identifying them. This was the case for all inducer types. We will discuss this aspect of the data further below. For now, we will concentrate on the differences between different inducer types.

Figure 3 shows distinct differences in the speed of processing of the different inducer types. For localisation, shapes defined by continuous physical contours, namely the long lines forming the outline triangle (c) and the pacmen with lines (b), were processed fastest (92 ms and 105 ms, respectively). When the physical contour was restricted to the corners of the triangular shapes, as was the case for the short lines (d) and pacmen (a), localisation took slightly, but significantly, longer (118 ms and 136 ms, respectively). The pacmen with the surrounding circles were slowest by far with an average threshold of 285 ms. Results for this inducer type also showed a larger variation within and between observers. Observers reported that this inducer type was most difficult, and that they frequently had to scan the display until they found the target. This is also apparent when looking at figure 1, where the amodally completed target (figure 1e) is much less visible than the other target types (figures 1a–1d).

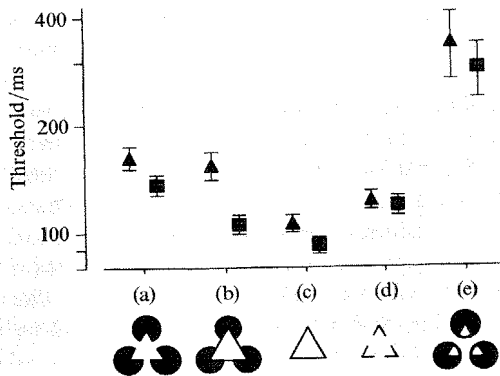


Figure 3. Average responses of fifteen practised observers for five different types of inducers (*x*-axis). Example stimuli, corresponding to those shown in figure 1, are shown at the bottom of the graph. The time necessary for correctly localising the target triangle (squares) or for correctly identifying its orientation (triangles) is plotted on the *y*-axis. Vertical bars represent ± 1 standard error of the mean.

The most surprising aspect of our data was a difference in the processing speed of the Kanizsa triangles [pacmen, type (a)] and the triangles defined by corners only [short lines, type (d)]. The former gave rise to a strong percept of illusory contours along the sides of the triangle; the isolated corners did not. Because of their perceptual salience, we expected the Kanizsa triangles to be detected and identified faster than or at least as fast as the corners. The opposite turned out to be the case. Subjects were faster in both localising and identifying the triangle defined by the corners only. Subjects required 136 ms to localise the Kanizsa triangle, and 118 ms for the triangle defined by the corners only ($t_{14} = 3.42$, $p < 0.01$). For identification, thresholds were 162 ms for the Kanizsa triangle and 136 ms for the triangle composed of corners ($t_{14} = 7.48$, $p < 0.01$). This was also the case when the whole contour was defined by luminance in the case of the pacmen with lines (b) and the long lines (c). The triangle was perceived faster when the pacmen inducers were not present. Subjects required 105 ms to localise the pacmen with lines, and only 92 ms for the complete triangles ($t_{14} = 3.79$, $p < 0.01$). For identification, thresholds were 154 ms for the Kanizsa triangle with lines and 105 ms for the complete triangles ($t_{14} = 7.42$, $p < 0.01$).

This basic pattern of results was fairly independent of the type of mask used. We had run several earlier series of experiments with different mask types (in addition to the ones shown in figure 1f). For example, we had chosen randomly oriented inducing elements as masking elements for all inducer types, and had observed the same ranking of thresholds. For the triangles defined by lines, we had also tested randomly oriented line segments, which did not affect thresholds significantly. The only significant effect of a mask we observed was for the pacmen with the lines. If only two lines are extended, at the mouths of the masking pacmen, the difference between localisation and identification thresholds was much smaller (22 ms) than above (49 ms), where six equally spaced lines were drawn. No other effects of different mask types were observed.

2.2.2 Localisation versus identification. For all inducer types we found a difference between localisation and identification. This difference was approximately constant, so that all of the above results hold for both localisation and identification. On average, subjects were faster in the localisation task than in the identification task. This was true even though the information required to do the two tasks is essentially the same. Figure 4 is a plot of the difference between identification and localisation thresholds as a function of the absolute threshold for localisation. Different symbols are used for the different inducer types. Data for the pacmen with circles are not shown in this graph, since thresholds, and also variability, for that inducer type were much larger than for the other inducer types. Localisation was faster than identification for fifty-four out of sixty data points, and minimally slower for the other six. Identification thresholds were significantly higher than localisation thresholds ($t_{59} = 41.4$, $p < 0.001$), with a mean difference of 23 ms. This delay was not correlated with the absolute processing time. The correlation coefficient between localisation threshold and identification delay was basically zero ($\rho = -0.0077$, $p > 0.05$). Thus the data are compatible with the hypothesis of a constant delay between the two tasks.

It is quite possible that observers allocate different amounts of attention to the two different components of this dual task. Even though the order of responses was arbitrary, most subjects preferred to do the localisation response first. To circumvent this problem, we tested the two tasks in separate experiments for three of the above subjects. For these three subjects, the average dual-task thresholds were 106 ms for localisation and 126 ms for identification ($\Delta t = 20$ ms). When obtained separately, the localisation threshold was 105 ms and the identification threshold was 116 ms ($\Delta t = 11$ ms). The difference in thresholds remained, although smaller, and was therefore not caused by attentive factors alone.

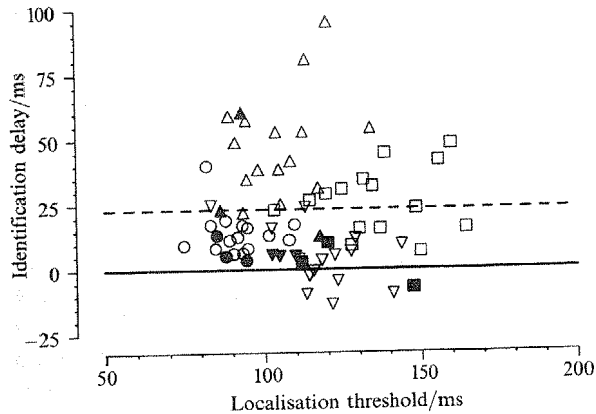


Figure 4. Comparison of thresholds for localisation and identification for the fifteen observers from figure 3. Localisation threshold is plotted on the x-axis. The difference between identification and localisation thresholds is plotted on the y-axis. The thick line at zero indicates identical localisation and identification thresholds. The dashed horizontal line shows the mean difference of 23 ms. Different symbols indicate four different inducer types (squares, pacmen; upward-pointing triangles, pacmen with lines; circles, long lines; downward-pointing triangles, short lines). Filled symbols refer to results from experiments in which localisation and identification were tested separately.

2.3 Discussion

The results of experiment 1 show that the early processing of shape information is not enhanced by the formation of illusory contours. Since triangles defined by pacmen [Kanizsa triangles, types (a) and (b)] are processed more slowly than triangles defined by line segments [types (d) and (c)], it seems that the pacman shape interferes with the process that connects and groups the components of the triangle. However, it has to be kept in mind that the difference in processing time could be due to several factors. One way to think about the computations involved is to assume that initially all inducing elements are processed separately and independently in parallel. This assumption makes sense since the elements are displayed at different retinal locations. Subsequently a process of contour continuation is automatically initiated for all contour segments. This continuation process takes some time until connections between the inducers making up the target shape are found. These connections then become available to the next stage, where shape information is extracted. Accordingly, differences in processing time could arise at the level where the continuation process is initiated, or at the interpolation process. Since processing for the long lines, which formed complete triangles defined by physical contours, was faster than for the short lines, where the triangles had gaps, we assume that the continuation process bridging these gaps takes a significant amount of time. Consistent with results by Davis and Driver (1994) and Gurnsey et al (1996), an extended visual search was required only for the pacmen with the surrounding circles. Experiment 2 was devised to determine the exact dynamics of the spatial interpolation between the gaps. Specifically, we were interested whether the aforementioned differences between pacmen-defined and line-defined stimuli were due to differences in the speed of interpolation, or due to differences in latency that could be caused by the different spatial configurations.

3 Experiment 2: Interpolation speed

3.1 Methods

Methods were identical to the ones used in experiment 1, except for the following. Stimuli were defined by line segments of different length or pacmen of varying sizes. The length of the segments of inducer type (d) was specified as percentage of the

distance between the corners of the target triangle, since that 'support ratio' has been shown to play an important role in determining the perceived strength of visual interpolation (Shipley and Kellman 1992; but see Soriano et al 1996). For pacmen the support ratio is defined as the ratio of the diameter of the pacmen to the distance between two pacmen. A support ratio of 100% means that the three pairs of lines forming the target triangle were physically connected [as in type (c) of experiment 1]. We will sometimes specify the stimulus in terms of the relative gap length, which is given by $100\% - \text{support ratio}$. A support ratio of 66% [as in type (d) of experiment 1] means that the sides of the target triangle had gaps in the middle whose length was 34% of the distance between the corners of the triangle. For this special case, the resulting gap length was 0.85 deg of visual angle. Stimuli were used with support ratios of 100%, 80%, 66%, 50%, and 40%. We also tried several support ratios smaller than 40% (in our case 1.5 deg), but subjects could no longer perform the task within reasonable durations (< 500 ms) and without scanning the display. All four of the observers had participated in experiment 1, including JR, one of the authors.

3.2 Results

In figure 5 thresholds for the triangles defined by lines [type (d)] are plotted as a function of the support ratio. Squares indicate thresholds for localisation, triangles thresholds for identification. There is a monotonic decrease in thresholds with increasing support ratio. Thresholds decreased approximately in a linear fashion for support ratios of 50% or larger. For smaller support ratios the amount of time required for localisation and identification increased exponentially and the task became impossible. We therefore constrained our analysis to support ratios larger than or equal to 50%. The slopes of the initial linear decrease were roughly similar for all subjects and similar for the localisation and identification tasks. The slope of the regression relating thresholds to relative gap length ($100\% - \text{support ratio}$) specifies how much time (in ms) is necessary to interpolate 1% of the total distance between the corners of the triangles. This total distance was 2.55 deg, as in experiment 1. For the localisation and identification data we found a slope of $0.74 \text{ ms } (\% \text{ gap length})^{-1}$, corresponding to 29 ms deg^{-1} .⁽³⁾ This regression accounted for 63% of the variance in the individual data.

Similar results were obtained for the pacmen-type stimuli, as shown in figure 6. The slope of the average observer was $1.21 \text{ ms } (\% \text{ gap length})^{-1}$, corresponding to 47.6 ms deg^{-1} .

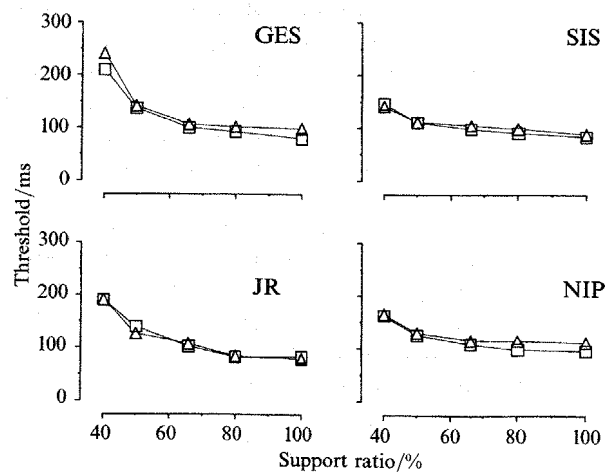


Figure 5. Spatial interpolation of gaps between line segments as a function of support ratio for four different observers. The support ratio as a percentage of the distance between the corners of the triangle is plotted on the x-axis. A support ratio of 100% corresponds to 2.55 deg of visual angle. Thresholds for correctly localising (open squares) or identifying (open triangles) the stimuli are plotted on the y-axis. Data are from four highly practised subjects.

⁽³⁾ Earlier work (Shipley and Kellman 1992) has shown that many aspects of illusory contour perception are scale invariant and depend on support ratio only. Since we used a fixed scale, we specify the speed of interpolation in terms of support ratio and visual angle.

The regression accounted for 61% of the variance. The response patterns of the subjects are quite similar to the pattern shown in figure 5 for the stimuli defined by corners. Subjects JR and GES showed a larger increase at the smaller support ratios both for corners and for pacmen stimuli.

When averaged across all four observers, the pattern of results looks quite similar under all conditions. The slopes for the two regression lines for the corners and the pacmen were not significantly different ($t_{12} = 0.77$, $p > 0.1$). The best-fitting common slope was 38.3 ms deg^{-1} and explained 77% of the variance of the averaged data. For the given distance between inducers of 2.55 deg it takes 38.3 ms to interpolate 1 deg. This holds for support ratios larger than or equal to 50%. When the distance between inducers increases, the time required to interpolate the segments increases exponentially, and the task becomes impossible at support ratios smaller than 40%.

Four other practised observers, whose data are not shown, were tested under slightly different mask conditions (randomly oriented inducers instead of pinwheels or wheels). Their results agree in all respects with the results shown above.

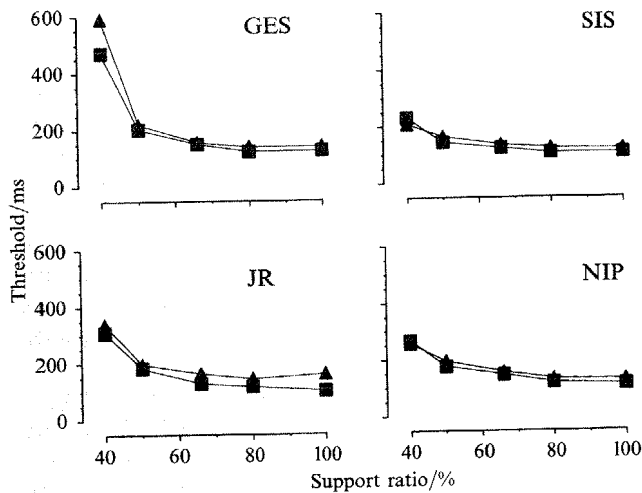


Figure 6. Spatial interpolation of gaps between pacmen as a function of support ratio. The support ratio is plotted on the x-axis as a percentage of the distance between the corners of the triangle. Thresholds for correctly localising (filled squares) or identifying (filled triangles) the stimuli are plotted on the y-axis. Data are from the same four observers as in figure 5.

4 Experiment 3: Isoluminant stimuli

It has often been argued in the past that form perception is significantly impaired when stimuli are defined by chromatic contrast exclusively (for a review, see Livingstone and Hubel 1988). This had been found earlier for illusory contours, when the inducers are defined by isoluminant variations (Gregory 1977). However, isoluminant stimuli were usually compared with high-contrast luminance stimuli. Isoluminant stimuli, by definition, do not have any luminance contrast. The excitations of L-cones and M-cones are balanced to keep their sum, which corresponds to luminance, constant. We can use this cone modulation to calculate a contrast for each cone type. For luminance stimuli, contrasts of 100% in all three cone types can be achieved. Because of the large overlap in the spectral sensitivities of L-cones and M-cones, the maximal cone contrast is much reduced when the sum of the cone excitations has to remain constant under conditions of isoluminance (MacLeod and Boynton 1979). The upper limit for a symmetric modulation around a neutral grey is about 34% RMS cone contrast, and values achieved on typical CRT monitors are at about 10% RMS cone contrast. This is a log unit less than the maximal contrast for luminance stimuli. Because contrast is an important factor in almost all visual tasks, it has been argued that a performance difference was mostly due to contrast differences between luminance and isoluminant stimuli (Webster et al 1990; Krauskopf and Farell 1991). The goal of experiment 3 was to test this hypothesis

for illusory-contour perception. We therefore compared performance for complete contours and illusory contours when stimuli were defined by luminance contrast or by chromatic contrast alone (isoluminance).

4.1 Methods

In experiment 3, luminance contrasts of 100% and 10% were used and compared with an isoluminant condition where stimuli were presented in red (CIE x, y : 0.39, 0.30) at the same luminance (30 cd m^{-2}) as the grey background (CIE x, y : 0.32, 0.34). The averaged Weber contrast in L-cones and M-cones achieved under this isoluminant condition was about 10%, roughly comparable to the low-contrast luminance condition. Experiments were run with Kanizsa triangles defined by pacmen [illusory contours, type (a) of experiment 1] and triangles defined by lines connecting their corners [real contours, type (c) of experiment 1].

Fifteen university students participated in this experiment. They were tested for thirty to fifty trials at seven presentation times for each of the six stimuli [standard, low contrast, and isoluminant for both type (a) and type (c)]. All had normal or corrected-to-normal visual acuity and normal colour vision.

4.2 Results

Figure 7 shows performance for the two types of contour (figure 7a, real; figure 7b, illusory) for the three different contrast conditions. Thresholds are shown for localisation (filled bars) and identification (open bars). The pattern of results is once again identical for both tasks. Under all conditions, performance is better for high-contrast luminance stimuli than for the isoluminant stimuli. However, performance for the low-contrast stimuli depends on the type of contour used. It can be seen from figure 7a that, for the triangles defined by a real contour, performance for low-contrast luminance stimuli was about equal to that for isoluminant stimuli (low-contrast luminance, 245.9 ms; isoluminant, 287.1 ms; $t_{14} = 1.62, p > 0.05$). In comparison, high-contrast luminance stimuli (105.4 ms) led to faster localisation and identification than low-contrast luminance stimuli ($t_{14} = 5.83, p < 0.001$) and isoluminant stimuli ($t_{14} = 5.88, p < 0.001$).

This was not observed for the illusory-contour stimuli, as seen in figure 7b. There was no difference in performance for high-contrast (169.8 ms) and low-contrast (184.4 ms) luminance-defined stimuli ($t_{14} = 1.60, p > 0.05$), but isoluminant stimuli required longer durations for localisation and identification than both (338.2 ms; $t_{14} = 7.75$ and $t_{14} = 6.86$, respectively; $p < 0.001$).

4.3 Discussion

The results of experiment 3 indicate that there is a differential impairment for isoluminant stimuli compared with low-contrast luminance only for the pacmen-induced stimuli. When the contours are complete, the difference between low-contrast luminance triangles and isoluminant triangles was negligible. The conclusion would be that it is not contour perception per se that is impaired at isoluminance, but contour interpolation. However, the interpretation is slightly more complicated than that.⁽⁴⁾ Interestingly, the relative performance for pacmen and triangles reverses for low-contrast and high-contrast luminance stimuli. At high contrasts, such as used in experiment 1, performance is much faster for complete contours than it is for pacmen. However, at low contrasts this is no longer true: the pacmen are processed faster than the complete triangles. This makes it difficult to quantitatively evaluate the results of the comparison with isoluminant stimuli. What is clear is that isoluminant stimuli behave qualitatively differently from low-contrast luminance stimuli, and that both chromatic and luminance contrast can be used for contour interpolation.

⁽⁴⁾ We would like to thank an anonymous reviewer for pointing this out.

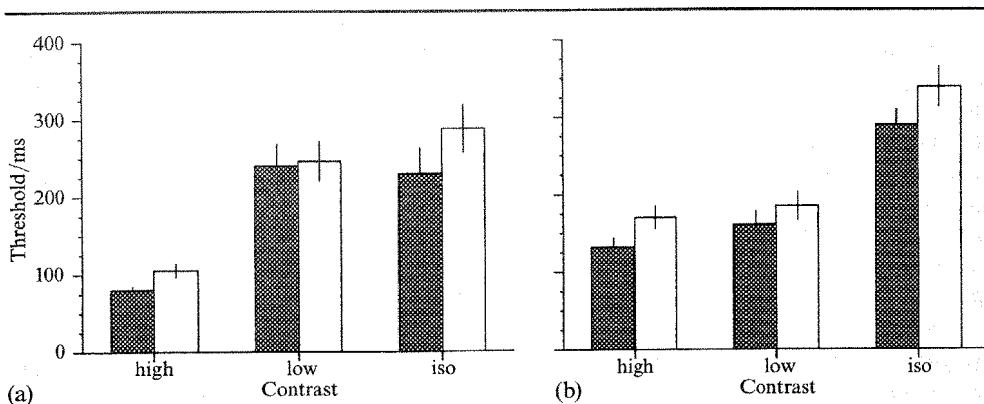


Figure 7. Comparison between luminance-defined inducers and isoluminant inducers. Average data from fifteen observers are shown. Thresholds for correctly localising (filled bars) or identifying (open bars) the target shapes are plotted on the y -axis. Stimuli were presented in white on a grey background (high, 100% luminance contrast), in light grey on a grey background (low, 10% luminance contrast), or isoluminant red on a grey background (iso, 0% luminance contrast, 10% RMS-cone contrast). (a) Inducers were 'real' triangles defined by lines; (b) inducers were illusory Kanizsa triangles defined by pacmen.

5 General discussion

In summary, we have shown that shape localisation and identification proceeds fastest for the simplest type of stimulus: triangles defined by lines connecting their corners. The pacmen used in the Kanizsa triangles interfered with contour interpolation, but not nearly as much as an outline circle around the pacmen [type (e)]. Since no illusory contour arises from the line segments, we conclude that the formation of illusory contours does not enhance the initial processes required to extract the triangular shape. The temporal dynamics of contour interpolation showed an approximately linear increase in processing time with decreasing support ratios for small and medium-sized gaps. For larger gaps the time necessary to bridge them increased steeply. The speed of contour interpolation was not significantly different for shapes defined by pacmen and lines, supporting the notion that only the initiation of contour interpolation is slower for the pacmen, not the speed of interpolation. Last, we found that contour interpolation was possible at isoluminance, but that it is qualitatively different from the processing of low-contrast luminance stimuli.

Several other researchers have investigated the time course of various aspects of illusory contours. Reynolds (1981) showed that it takes about 100 ms for an illusory contour to be perceived when viewing a single Kanizsa triangle with a postexposure mask. In his task subjects had to estimate the qualitative appearance of the triangle. Ringach and Shapley (1996) investigated the presentation time necessary to use the illusory-contour information in a shape-discrimination task. They found that, for durations of about 100 ms and longer, shape-discrimination performance was close to that for real contours. In their experiments, no significant difference emerged between modally and amodally completed Kanizsa squares (pacmen and pacmen with circles, respectively) for the precision with which the shape discrimination task could be done. However, to achieve the same level of performance the exposure duration had to be 50 ms longer for the amodal completion. We found a much larger difference in the speed of processing of amodally completed Kanizsa triangles [type (e)]. However, in Ringach and Shapley's experiment only the target was presented, whereas in our task the target shape (triangle) was displayed amidst a set of distractors. Davis and Driver (1994) have shown that this requires a serial search for amodally completed illusory figures, but can be done in parallel for modally completed figures. Therefore the necessary visual search for the target might account for the difference in results.

One interesting aspect of our data is that simple high-contrast line segments led to faster processing than Kanizsa triangles. It seems that any type of inducing pattern that is not collinear with the side of the triangle interferes with the initiation of contour interpolation, even if the presence of these inducers leads to a more salient percept in the end, through the formation of illusory contours and surfaces. This result implies that the interpolation process occurs independently of the formation of illusory contours and the various perceptual effects like brightness enhancements that go with it. A similar independence has been found between the formation of illusory contours and the facilitation of small light targets positioned between the inducing elements (Dresp 1993).

The contour-interpolation process itself seems to follow the Gestalt law of good continuation (Wertheimer 1923). The most natural candidate for a neural implementation of such a continuation process is an excitatory propagation of activation among groups of neurons whose receptive fields are aligned and similarly oriented, and inhibition between neurons with different preferred orientations. Therefore contours orthogonal to the side of the triangle, such as the circles around the pacmen [type (e)], interfere with this spread. Similarly, the standard pacmen in the Kanizsa triangle are oriented orthogonally to the sides of the triangle and therefore might interfere with the completion process along the side of the contour. Recent psychophysical experiments (Dresp 1993; Field et al 1993; Kapadia et al 1995; Dresp and Grossberg 1997) have characterised the spatial properties of the interpolation process. The more general neural basis for interpolation might lie in the effects of remote stimuli on the neuronal tuning properties. Such effects of stimuli presented outside of the classical receptive field of the neuron have come under investigation recently (Gilbert and Wiesel 1990; Kapadia et al 1995; Sillito et al 1995; Levitt and Lund 1997) and are probably due to long-range interactions in the visual system (Spillmann and Werner 1996).

In some of the early physiologically motivated models of illusory-contour perception (Peterhans and von der Heydt 1989) it was assumed that during contour interpolation the contributions of illusory and real contours are added. If that were the case, then the Kanizsa triangle in our experiment [type (a)] should have led to better performance than the stimulus defined merely by corners of a triangle [type (d)]. This was clearly not the case. Most current models (Grossberg and Mingolla 1985; Heitger and von der Heydt 1993; Grossberg 1994) consist of two stages. Initially boundaries are extracted and at the second stage object features such as brightness are integrated. Illusory-contour formation takes place only after the extraction of the whole boundary is finished, which is in accordance with our results. Some models (Heitger and von der Heydt) postulate an excitatory grouping process in the orientation orthogonal to the ending of a contour, since these endings, when properly aligned, also elicit illusory-contour responses (see Leshner and Mingolla 1993). Whereas there is a certain advantage to explaining both of these types of illusory contour by the same processes, our results indicate that there might be different underlying mechanisms.

We did not find a significant difference in the speed of contour interpolation between the triangles defined by line segments and the Kanizsa triangles. This could be due to the small number of observers (four) who performed this lengthy task. But if the interpolation speeds are indeed identical, this would strongly suggest that one and the same neural mechanism is underlying interpolation for both inducer types. Significant differences between stimulus types were found in the latency of the interpolation process only. The latency seems to depend on the spatial configuration of the inducers.

One peculiar aspect of our data is the consistent advantage of localisation over identification of the triangles. This result is not trivial since the same information is required to do both tasks. The localisation can only be done through the extraction of the shape of the objects. Information about all three corners of the object has to be combined. There are several possible explanations. A hypothesis that has often been

suggested is that processing proceeds from a coarse to a fine scale (Marr 1982). Whereas the completion of the contour can be detected at the very coarse scale, this is not the case for the orientation of the triangle. Low-pass filtered images of Kanizsa triangles (Ginsburg 1975) reveal that the orientation of the triangles cannot be reliably determined without the high-spatial-frequency information. Another possible explanation would be that different visual subsystems are involved in localisation and identification (Mishkin et al 1983), and that the localisation or 'where' system is faster than the identification or 'what' system. One hypothesis we can reject is that subjects simply allocate more attention to the detection process than to identification in this dual task. We found similar results when detection and identification were tested in separate blocks of trials. However, on the basis of our current data we cannot discriminate between the first two hypotheses.

Our results with isoluminant stimuli show that form processing per se is not impaired at isoluminance, at least not for the stimuli used here. They also demonstrate that the contrast of the stimulus is an important variable for performance, even when luminance stimuli of different contrast are compared.

Acknowledgments. We would like to thank Heiko Neumann, Dan Kersten, Dario Ringach, and Bob Shapley for valuable discussions, and Doris Braun and Alexander Grunewald for comments on an earlier version of this manuscript. We are also grateful to Birgitta Dresch, Ennio Mingolla, and an anonymous reviewer for their critical reviews, and to Lothar Spillmann for numerous helpful suggestions. Joel Brown was supported by a stipend from the German Academic Exchange Service (DAAD). Karl R Gegenfurtner was supported by a Habilitationsstipendium from the German Research Council (DFG Ge 879/2-1).

References

- Davis G, Driver J, 1994 "Parallel detection of Kanizsa subjective figures in the human visual system" *Nature (London)* **371** 791-793
- Dresch B, 1993 "Bright lines and edges facilitate the detection of small light targets" *Spatial Vision* **7** 213-225
- Dresch B, Bonnet C, 1991 "Psychophysical evidence for low level processing of illusory contours and surfaces in the Kanizsa square" *Vision Research* **31** 1813-1817
- Dresch B, Bonnet C, 1993 "Psychophysical measures of illusory form perception: further evidence for local mechanisms" *Vision Research* **33** 759-766
- Dresch B, Bonnet C, 1995 "Subthreshold summation with illusory contours" *Vision Research* **35** 1071-1078
- Dresch B, Grossberg S, 1997 "Contour integration across polarities and spatial gaps: from local contrast filtering to global grouping" *Vision Research* **37** 913-924
- Ejima Y, Takahashi S, 1988 "Illusory contours induced by isoluminant chromatic patterns" *Vision Research* **28** 1367-1377
- Field D J, Hayes A, Heiss R F, 1993 "Contour integration by the human visual system: evidence for a local 'association field'" *Vision Research* **33** 173-193
- Gilbert C D, Wiesel T N, 1990 "The influence of contextual stimuli on the orientation selectivity of cells in primary visual cortex of the cat" *Vision Research* **30** 1689-1701
- Ginsburg A P, 1975 "Is the illusory triangle physical or imaginary?" *Nature (London)* **257** 219-220
- Gregory R, 1977 "Vision with isoluminant colour contrast: I. A projection technique and observations" *Perception* **6** 113-119
- Grosz D H, Shapley R M, Hawken M J, 1993 "Macaque V1 neurons can signal 'illusory' contours" *Nature (London)* **365** 550-552
- Grossberg S, 1994 "3-D vision and figure-ground separation by visual cortex" *Perception & Psychophysics* **55** 48-120
- Grossberg S, Mingolla E, 1985 "Neural dynamics of perceptual grouping: textures, boundaries, and emergent segmentations" *Perception & Psychophysics* **38** 141-171
- 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
- Heitger F, Heydt R von der, 1993 "A computational model of neural contour processing: Figure ground segregation and illusory contours", in *Proceedings of the 4th International Conference on Computer Vision* (Los Alamitos, CA: IEEE Computer Society Press) pp 32-40

- Heydt R von der, Peterhans E, 1989 "Mechanisms of contour perception in monkey visual cortex. I. Lines of pattern discontinuity" *Journal of Neuroscience* **9** 1731–1748
- Heydt R von der, Peterhans E, Baumgartner G, 1984 "Illusory contours and cortical neuron responses" *Science* **224** 1260–1262
- Hirsch J, De La Paz R L, Relkin N R, Victor J, Kim K, Li T, Borden P, Rubin N, Shapley R, 1995 "Illusory contours activate specific regions in human visual cortex: evidence from functional magnetic resonance imaging" *Proceedings of the National Academy of Sciences of the USA* **92** 6469–6473
- Kanizsa G, 1979 *Organization in Vision* (New York: Praeger)
- Kapadia M K, Ito M, Gilbert C D, Westheimer G, 1995 "Improvement in visual sensitivity by changes in local context: parallel studies in human observers and in V1 of alert monkeys" *Neuron* **15** 843–856
- Kojo I, Liinasuo M, Rovamo J, 1993 "Spatial and temporal properties of illusory figures" *Vision Research* **33** 897–901
- Krauskopf J, Farell B, 1991 "Vernier acuity: effects of chromatic content, blur and contrast" *Vision Research* **31** 735–749
- Leshner G W, Mingolla E, 1993 "The role of edges and line-ends in illusory contour formation" *Vision Research* **33** 2253–2270
- Levitt J B, Lund J S, 1997 "Contrast dependence of contextual effects in primate visual cortex" *Nature (London)* **387** 73–76
- Li C, Guo K, 1995 "Measurements of geometric illusions, illusory contours and stereo-depth at luminance and color contrast" *Vision Research* **35** 1713–1720
- Livingstone M S, Hubel D H, 1988 "Segregation of form, color, movement, and depth: anatomy, physiology, and perception" *Science* **240** 740–749
- MacLeod D I A, Boynton R M, 1979 "Chromaticity diagram showing cone excitation by stimuli of equal luminance" *Journal of the Optical Society of America* **69** 1183–1186
- Marr D, 1982 *Vision* (San Francisco, CA: W H Freeman)
- Mishkin M, Ungerleider L G, Macko K A, 1983 "Object vision and spatial vision: two cortical pathways" *Trends in Neurosciences* **6** 414–417
- Peterhans E, Heydt R von der, 1989 "Mechanisms of contour perception in monkey visual cortex. II. Contours bridging gaps" *Journal of Neuroscience* **9** 1749–1763
- Petry S, Meyer G, 1987 *The Perception of Illusory Contours* (New York: Springer)
- Redies C, Crook J M, Creutzfeld O D, 1986 "Neuronal responses to borders with and without luminance gradients in cat visual cortex and dorsal lateral geniculate" *Experimental Brain Research* **61** 469–481
- Reynolds R I, 1981 "Perception of an illusory contour as a function of processing time" *Perception* **10** 107–115
- Ringach D L, Shapley R M, 1996 "Spatial and temporal properties of illusory contours and amodal boundary completion" *Vision Research* **36** 3037–3050
- Shapley R, Gordon J, 1987 "The existence of interpolated illusory contours depends on contrast and spatial separation", in *The Perception of Illusory Contours* Eds S Petry, G Meyer (New York: Springer) pp 109–115
- Shipley T, Kellman P, 1992 "Strength of visual interpolation depends on the ratio of physically specified to total edge length" *Perception & Psychophysics* **52** 97–106
- Sillito A M, Grieve K L, Jones H E, Cudeiro J, Davis J, 1995 "Visual cortical mechanisms detecting focal orientation discontinuities" *Nature (London)* **378** 492–496
- Soriano M, Spillmann L, Bach M, 1996 "The abutting grating illusion" *Vision Research* **36** 109–116
- Spillmann L, Dresch B, 1995 "Phenomena of illusory form: can we bridge the gap between levels of explanation?" *Perception* **24** 1333–1364
- Spillmann L, Werner J S, 1996 "Long-range interactions in visual perception" *Trends in Neurosciences* **19** 428–434
- Webster M A, De Valois K K, Switkes E, 1990 "Orientation and spatial-frequency discrimination for luminance and chromatic gratings" *Journal of the Optical Society of America A* **7** 1034–1049
- Wertheimer M, 1923 "Untersuchungen zur Lehre von der Gestalt, II" *Psychologische Forschung* **4** 301–350