ACTA NEUROBIOLOGIAE EXPERIMENTALIS

Research Paper Acta Neurobiol Exp 2013, 73: 417–429

Perceptual mislocalization of a single set of the Müller–Lyer wings

Aleksandr Bulatov*, Lina Mickienė, Natalja Bulatova, and Arūnas Bielevičius

Institute of Biological Systems and Genetics Research, Lithuanian University of Health Sciences, Kaunas, Lithuania, *Email: bulatov@vision.kmu.lt

In the present communication, a possible role of perceptual displacements of stimulus elements in the occurrence of visual illusions of extent has been considered. In psychophysical experiments with a single set of Müller–Lyer wings, subjects were asked to place an imaginary reference rectangle into a position that made the apex of the wings appear to be at the rectangle center. Three different stimulus parameters (the length, internal angle, or tilt angle of the wings) were used as independent variables in different series of experiments. It was demonstrated that the magnitude of perceptual displacements of stimulus terminator is commensurate with that of illusions of extent obtained in our previous studies of full versions of illusory figures. Good correspondence between the experimental data and the predictions of our computational model of automatic centroid extraction strongly supported the suggestion that the effects of centroid extraction are powerful enough to be considered as one of the main causes of illusions of extent of the Müller–Lyer type.

Key words: the Müller–Lyer illusion, contextual distracter, positional shift, centroid

INTRODUCTION

Though the geometric illusions of the Müller–Lyer type (identical spatial intervals flanked by different contextual objects appear to be different in size, Fig. 1) are routinely classified as illusions of length, evidence from a number of studies suggest that the strength of these perceptual distortions is mainly influenced by the features of the contextual flanks used and may be caused by local positional shifts of stimulus terminators (i.e., items designating the ends of spatial intervals) rather than by a uniform contraction or expansion of the whole stimulus pattern. It has been shown that these illusions survive deletion of noncritical stimulus elements such as the shaft-line, and that even simplified figures composed of separate dots can cause quite substantial distortions (Greist-Bousquet and Schiffman 1981). Psychophysical studies of conventional Müller–Lyer and Judd figures with markers placed at various positions along the shaft have revealed that the effects of length difference are appreciable only for segments in the immediate vicinity of the wings apexes (Morgan et al. 1990, Post et al. 1998). Successive bisections of the Müller–Lyer figure shaft into eight equal-appearing parts demonstrated that only the areas comprising the arrowheads are particularly effective for the induction of the illusion (Predebon 2001). Substantial errors in perceived location were established for the Müller–Lyer illusions when wings were attached to only one side of the stimulus (Welch et al. 2004). Experiments with attaching shading to the Müller–Lyer and Judd figures yielded results which are consistent with the explanations of the illusion in terms of mislocalization of the wings-shaft intersections (Zanker and Abdullah 2004). Manipulations of Müller–Lyer illusion strength by using additional non-target dots demonstrated that illusion magnitude could be altered noticeably only when these extraneous dots were placed in close proximity to the wings' vertices (Searleman et al. 2005).

It should be noted, however, that in order to measure the effects of illusion, length-matching or bisection procedures were used in most of the previous studies. Even in experiments with stimuli comprising a reduced set of elements (Greist-Bousquet and Schiffman 1981, Greene and Nelson 1997, Welch et al. 2004, Predebon 2005) the ends of the spatial intervals were explicitly

Correspondence should be addressed to A. Bulatov, Email: bulatov@vision.kmu.lt

Received 27 February 2013, accepted 23 July 2013

designated (e.g., shaft end-points or dots), and the subjects were asked to judge whether these intervals were equal or unequal in size (i.e., lengths comparison rather than evaluation of positional shifts of stimulus elements has been performed). Therefore, it remains unclear whether perceptual mislocalization can arise for separate stimulus components (i.e., without regard to the length-matching or length-bisection tasks) and, if that is the case, whether these displacements are commensurate, when summed, with the magnitude of the illusion derived from judgments of extent for full versions of the stimuli. We believe that the results of experimental studies of the influence of the rotation of contextual flanks (distracters) on the magnitude of the perceptual errors in the right-angle adjustments can provide support for the suggestion about local positional shifts of stimulus terminators. It has been demonstrated (Bulatov et al. 2009a, 2012) that the distortions in perpendicularity judgments can be explained (assuming the existence of spatial integration within some circular areas surrounding the target stimulus elements) in terms of perceptual displacements of stimulus components, and that the magnitude of these distortions agrees rather well with that from the studies of the illusions of extent.

A number of investigators have posited that the distances between the centers-of-mass (centroids) of the objects' luminance distributions are routinely used by the visual system to evaluate the extent of their spatial separation (Westheimer and McKee 1977, Watt and Morgan 1983, Ward et al. 1985, Whitaker and Walker 1988, Morgan and Glennerster 1991, Hirsch and Mjolsness 1992, Morgan et al. 1994, Badcock et al. 1996, Whitaker et al. 1996, Akutsu et al. 1999, McGraw et al. 2003, Morgan 2010, Wright et al. 2011). According to the hypothesis of weighted pooling of positional signals (Morgan et al. 1990, Morgan and Glennerster 1991), this "centroid" bias in judgments of extent is causally related to the spatial integration of neural excitations evoked by the neighboring stimulus parts and can also explain the emergence of the Müller–Lyer (Morgan et al. 1990, Searleman et al. 2005), Poggendorff (Morgan 1999), Ponzo, and horizontal–vertical illusions (Searleman et al. 2009). The visual system fails to isolate the figure terminators from the adjacent contextual flanks because the pattern of neural excitation evoked by the flank overlaps with that caused by the terminator, thereby changing the overall excitation profile (thus, changing the locus of its centroid). In turn, the centroid bias leads to the perceptual positional shift of the terminator (i.e., the illusion of displacement) and the relative displacement of all stimulus terminators give rise to the illusion of extent. Thus, the "centroid" explanation implies the summation of contributions from each contextual distracter, and the effects of such additivity have been demonstrated in our previous studies of illusions (Bulatov et al. 1997, Bulatov and Bertulis 2005).

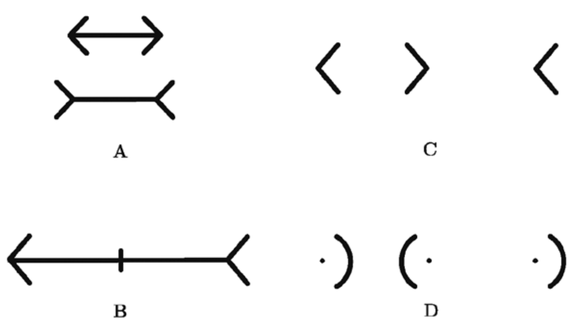


Fig. 1. Various versions of stimuli of the Müller–Lyer type. The classic Müller–Lyer (A) and the Judd figures (B) that give rise to the illusion of extent. Two modifications (having no shaft line) of the Brentano versions of illusory figures comprising different contextual flanks: the Müller–Lyer wings (C), and arcs of a circle (D).

In order to estimate whether the center-of-mass alterations are powerful enough to account for the data obtained in experiments with different variants of illusory figures of the Müller–Lyer type, a quantitative model of centroid extraction has been developed (Bulatov et al. 2009b, 2010). The model predictions closely matched the data collected in experiments with the Brentano modification of the Müller–Lyer type of illusory figures comprising different contextual flanks: either the Müller–Lyer wings, or vertical bars, or pairs of dots, or arcs of a circle (Bulatov et al. 2009b, 2010, 2011). However, the interpretation of the experimental data was associated with uncertainty because stimuli used in these studies comprised three clusters of contextual flanks and terminators which were located, generally, at different eccentricities in the visual field. In an ideal case (the same eccentricity for all three clusters), when assuming that each flanking object in the stimulus contributes to the illusory effect with the same weight, the strength of the illusion of extent (the difference in physical length between the left and wright intervals of the stimulus) should be four times greater than the positional shift caused by a single contextual flank: the lateral flanks yield two contributions, and the central one also provides two, because it changes the perceived length of both the left and wright intervals. However, under real conditions of experiments, all three stimulus parts cannot be simultaneously positioned with the same eccentricity, thus their contributions to the resulting illusion magnitude should differ (with larger values for the flanks more distant from the center of the fovea) and could not be established separately. For simplicity, the illusion magnitude was considered to be a result of the weighted summation of individual effects induced by each contextual flank – an averaged individual effect multiplied by a proportionality coefficient with the most probable value in the range from 1 to 4 (the upper limit of the range is estimated suggesting equal contributions from all three stimulus parts and the lower one is based on the assumption that the illusion could be caused by the perceptual positional shift of at least one stimulus terminator).

With the aim to diminish the uncertainty concerning the manifestation of positional shifts for separate stimulus terminators and for additional verification of the predictions of our "centroid" model, we have performed a psychophysical study with stimuli consisting of a single terminator (vertex of a single set of the Müller–Lyer wings) and distracter (the wings themselves). The task performed by observers during the experiments – to place the stimulus terminator in the center of an imaginary rectangle (i.e., without comparison of length of explicitly designated spatial intervals) – also was somewhat different from those used earlier. The main goal of the present study was to check the basic assumption of the "centroid" approach, i.e. to verify whether the positional displacements of stimulus terminator can emerge in the visual perception of a separate figural element (i.e., a single set of the Müller–Lyer wings), and whether the magnitude of these displacements can explain the strength of the illusion obtained for full versions of illusory figures (i.e., for the Brentano pattern having no shaft line and comprising three sets of the Müller–Lyer wings). Therefore, the detailed analysis of other well-known explanations of the illusions was left beyond of scope of the present communication.

METHODS

Subjects

Four observers (AK, EA, GN, and KS) participated, two of whom (GN and KS) were naïve to the purpose of the study and participated in psychophysical experiments for the first time. All participants reported normal or corrected-to-normal vision. Viewing was monocular, and the right eye was always tested irrespective of whether it was the leading eye or not. All observers gave their informed consent before taking part in the experiments that were performed according to the Declaration of Helsinki and were approved by the ethics committee of the Lithuanian University of Health Sciences.

Apparatus

The experiments were carried out in a dark room (the surrounding illumination <0.2 cd/m^2). A Sony SDM-HS95P 19-inch LCD monitor (spatial resolution 1 280×1 024 pixels, frame refresh rate 60 Hz) was used for stimulus presentation. A Cambridge Research Systems OptiCAL photometer was used to monitor luminance range calibration and gamma correction. A chin and forehead rest was used to maintain a constant viewing distance of 400 cm (at this distance each pixel subtended 0.25 min of arc). An artificial pupil with an aperture of 3 mm diameter was placed in front of the eye to reduce optical aberrations.

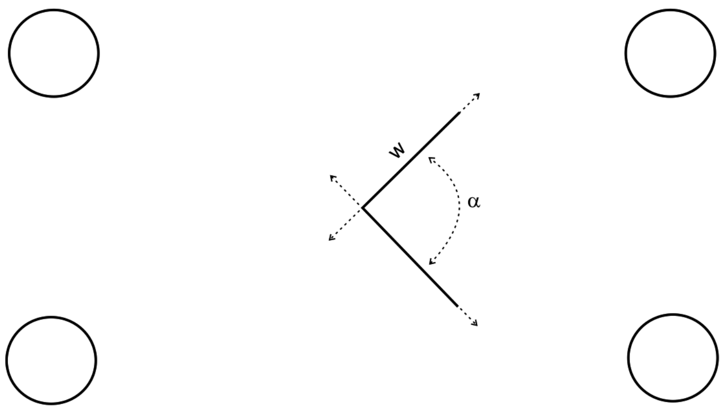
Stimuli were presented in the center of a round-shaped background 4° in diameter and 0.4 cd/m^2 in luminance (the monitor screen was covered with a black mask with a circular aperture to prevent observers from being able to use the edges of the monitor as a vertical/horizontal reference). For all the stimulus drawings, the Microsoft GDI+ anti-aliasing technique was applied to avoid jagged edges of lines.

Stimuli

The stimuli used (Fig. 2) consisted of a single set of the Müller–Lyer wings with their apex located on the horizontal axis of an imaginary rectangle with its corners coincided with centers of four small referential circles of radius 5 min of arc. Such a method of defining the vertices of the rectangle was chosen in order to escape any explicit designation of the ends of spatial intervals on the horizontal axis of the stimulus and make it more complicated for the observers to use the visually interpolated sides or diagonals of the rectangle

Three different stimulus parameters were used as independent variables in different series of experiments. In the first series, the length of the Müller–Lyer wings, *w* varied randomly in the range of ±12.5 min of arc (negative values correspond to the wings situated to the left of the apex); the internal angle (α=90°) and the tilt angle (Φ=0°) of the wings remained unchanged. In the second and in the third series of experiments, the internal angle, α or the tilt angle, Φ of the wings were randomly changed from 0° to 360°, respectively (wings length, *w* was fixed at 8 min of arc). The reasoning behind using the tilt angle as the independent variable is concerned with the crucial point in the "centroid" explanation which implies that the shifts of the stimulus terminators must be directed toward centers-of-mass of contextual flanks. Accordingly, one can expect that for figures with tilted flanks, e.g., relative to the horizontal axis, the magnitude of the terminator's illusory displacement along this axis should be proportional to the projection of the actual centroid bias onto the axis (i.e., modulated by the cosine function of the tilt angle of the flank's bisector), and the

A



B

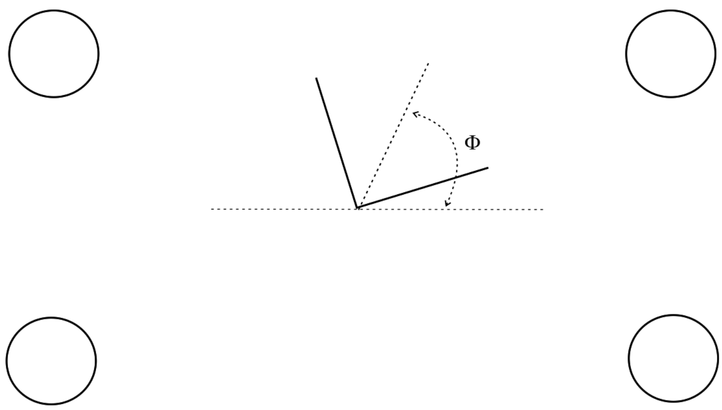


Fig. 2. Examples of stimuli used in the study. (A) (w) The length, or (α) the internal angle, or (B) (Φ) the tilt angle of the wings were used as independent variables in different series of experiments. The corners of an imaginary reference rectangle are defined by centers of four small circles. Actually, white line drawings (luminance 75 cd/m^2) were presented against a dark round-shaped background (4° in diameter and 0.4 cd/m^2 in luminance); dashed lines – the dimensions were not part of the actual display.

rotation of the flank around the terminator should evoke changes of the magnitude of the illusion of displacement by the cosine law (Bulatov et al. 2011).

The thickness (1 min of arc) of the lines forming the wings and circles, and their luminance (75 cd/m^2), remained constant throughout the study. In the first three series of experiments, the width and height of the reference rectangle were fixed at 100 and 63 min of arc, respectively. In the fourth series, in order to estimate the influence of the reference size, the rectangle width was changed to 50 min of arc.

Procedure

During the experimental run, the subjects were asked to manipulate the keyboard buttons "←"and "→" to displace simultaneously all the reference circles horizontally into a position that made the apex of the wings (with fixated location) appear to be at the center of an imaginary rectangle. A single button press varied the position of the reference by ±0.25 min of arc. The initial deviations from the zero-position (i.e., from the physical location of the apex of the wings) were randomized and distributed evenly within the range of ±5 min of arc, and the subjects did not know in advance whether the reference rectangle was actually displaced to the left or to the right.

The time of stimulus observation was not limited; the observers' eye movements were not monitored. The subjects were encouraged to maintain their gaze on the apex of the Müller–Lyer wings. Bias in positioning of the reference rectangle (determined after its apparent "centering" was established) was considered as the magnitude of the illusion of displacement (i.e., perceptual positional shift of stimulus terminator).

An experimental run comprised 60 stimulus presentations, i.e., 30 randomly distributed values of the independent variable were taken twice. A single experimental run lasted for about half an hour. Each observer carried out at least five repetitions of each experimental run on different days. Each data point represents the results of ten trials. In the data graphs the error bars depict ± one standard error of the mean (SEM).

Data analysis

For the quantitative assessment of the magnitude of centroid biases the experimental data were fitted (by the method of least squares) with the function derived from our model of the geometric illusions of extent, which has been described earlier in more detail (Bulatov et al. 2009b, 2010). The computational procedure of the model consists of two sequential stages: (1), a weighted spatial pooling of the neural excitations evoked by stimulus elements within a certain attentional window centered with stimulus terminator (the multiplication of the profile of the excitation by a circular Gaussian), and (2), calculation of the locus of centroid of the pooling by means of the 2D convolution of its spatial profile with that of the elongated receptive field (Gaussian weighting function along the short axis) of a certain summation unit. It was also assumed in the model that the size of attentional windows grows linearly with eccentricity in the visual field.

According to the model, the perceptual positional shift (along the horizontal axis) of the apex of the Müller–Lyer wings can be estimated by using the formula:

$$\delta(w,\alpha,\Phi) \cong C + \frac{\cos(\Phi)\cos(0.5\alpha)}{\sqrt{\pi B}\left(1+\cos^2(0.5\alpha)\right)} \frac{1-e^{-Bw^2\left(1+\cos^2(0.5\alpha)\right)}}{erf\left(w\sqrt{B}\right)} \quad (1)$$

where δ is the positional shift; w is the wing length; α and Φ, the internal angle and the tilt angle of the wings, respectively; $B = 1/2\sigma^2$, and C are free parameters representing the spread (σ) of the Gaussian profile of corresponding attentional pooling window (area of centroid extraction), and some arbitrary constant (bias along ordinate axis), respectively.

One can expect that applying of Formula 1 to the experimental data would enable the estimation (parameter B) of the spread of the relevant area of centroid extraction, and that the estimations acquired with three different types of independent variable (either the length, or the internal angle, or the tilt angle of the wings) should not differ significantly.

RESULTS

Four series of experiments were performed. The aim of the first series was to determine quantitatively the dependence of the magnitude of the perceptual positional shifts of stimulus terminator (illusion of displacement) on the length of the wings, w. The length of the wings varied randomly in the range of ±12.5 min of arc; the internal angle (α) and the tilt angle (Φ) of the wings were fixed at 90º and 0º, respectively. The width and height of the reference rectangle were fixed at 100 and 63 min of arc, respectively. All four subjects (AK, EA, GN, and KS) participated in this series of experiments.

According to the model's predictions (Formula 1), it was expected that for relatively short wings the magnitude of the illusion should increase in an approximately linear manner, whereas for longer wings the linearity should be violated, and a tendency to saturation should appear because of attenuation of influence of the more distant wing parts in the periphery of the area of centroid extraction.

For all subjects, the experimental data obtained (Fig. 3, circles) show a monotonic growth of the absolute value of illusion magnitude with increase of the length of the wings from 0 to about ±6 min of arc. For this range of wing lengths the results are quite similar for all subjects. However, for the longer wings the degrees of deviation from linearity in the experimental curves for different subjects can be seen.

In the second series of experiments, the internal angle of the wings (α) was varied randomly from 0° to 360°. The length and the tilt angle of the wings were fixed at 8 min of arc and 0°, respectively; dimensions of the reference rectangle remained unchanged (100×63 min of arc). The same four subjects participated in this series.

According to the model's predictions, experimental curves with a shape similar to a cosine of half the internal angle would be expected. Also, some deviations from the cosine law ought to be present, because Equation 1, besides the cosine function includes other sufficiently complex parts (e.g., Gaussian function) which depend on the internal angle of the wings.

The experimental data obtained (Fig. 4, circles) show nearly symmetrical curves with two parts comprising positive and negative values. The largest magnitudes of the illusion (the absolute values are approximately 2–3 min of arc for different subjects) were

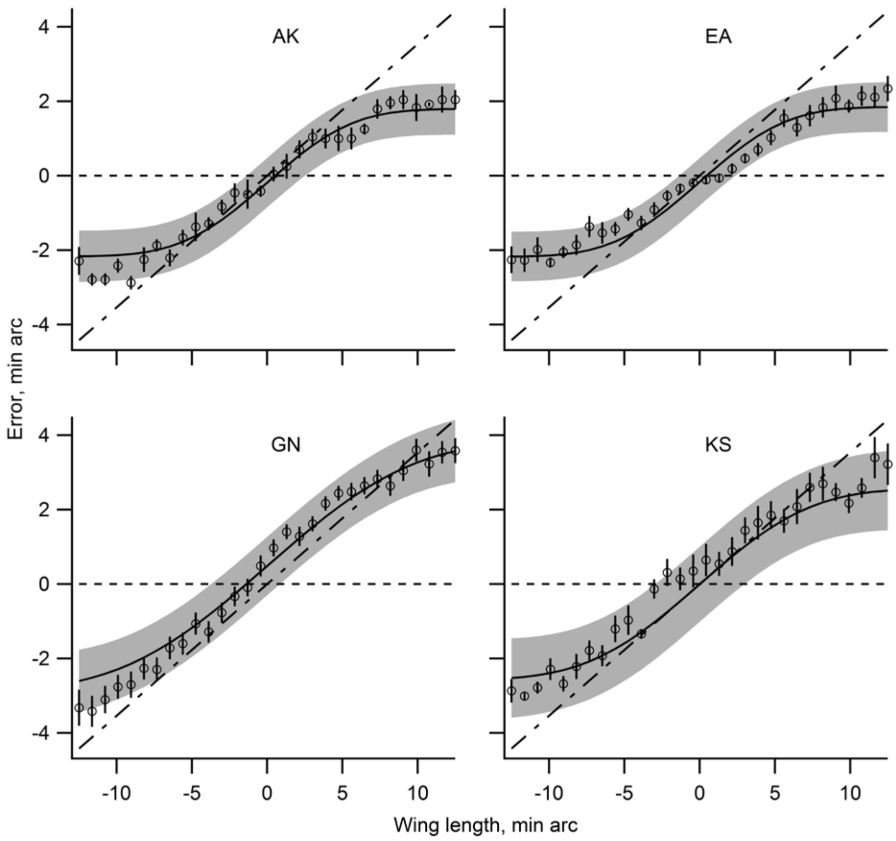


Fig. 3. Illusion of displacement as a function of the length of the wings (w). Four subjects (AK, EA, GN, and KS) tested. Solid curves, and gray bands, the least squares fitting by Formula 1, and confidence intervals for predicted values, respectively. Dashed-dotted lines – the magnitude of illusion for an infinitely large attentional window. The internal angle (α) and the tilt angle (Φ) of the wings were fixed at 90º and 0º, respectively; the dimensions of the reference rectangle were 100×63 min of arc. Error bars are ± one standard error of the mean (SEM).

established for the acute internal angles of the wings (the values of α nearly 0° and 360°). When the internal angle approached 180°, the magnitude of the perceptual positional shifts of the stimulus terminator decreased to zero.

The aim of the third series of experiments was to check whether the rotation of a single contextual distracter around the terminator causes any cosinusoidal changes of the magnitude of its horizontal perceptual displacements. The length and the internal angle of the wings were fixed at 8 min of arc and 90°, respectively; dimensions of the reference rectangle remained the same (100×63 min of arc) as in the previous series of experiments. The same four observers participated.

As can be seen in Figure 5, the experimental results for all subjects show curves similar to the cosine function. The illusion maxima (the absolute value is approximately 2–3 min of arc for different subjects) were established with distracter orientations close to horizontal (bisector tilt angle, Φ about 0° and 180°). The illusion decreased to zero when the tilt angle approached 90° and 270°.

In order to evaluate the influence of the reference rectangle size on illusion magnitude, a fourth series of experiments were performed. The width of the reference rectangle was reduced to half (50 min of arc) of its original size and the procedures of the previous experiments were repeated with two subjects (AK and EA) (the first three rows of Fig. 6, filled symbols).

As can be seen from the graphs, the experimental results for both subjects are quite similar to those obtained in the previous three series (the first three rows of Fig. 6, open symbols). For quantitative verification of this similarity, paired *t*-tests were applied at each data point to compare the results of the two

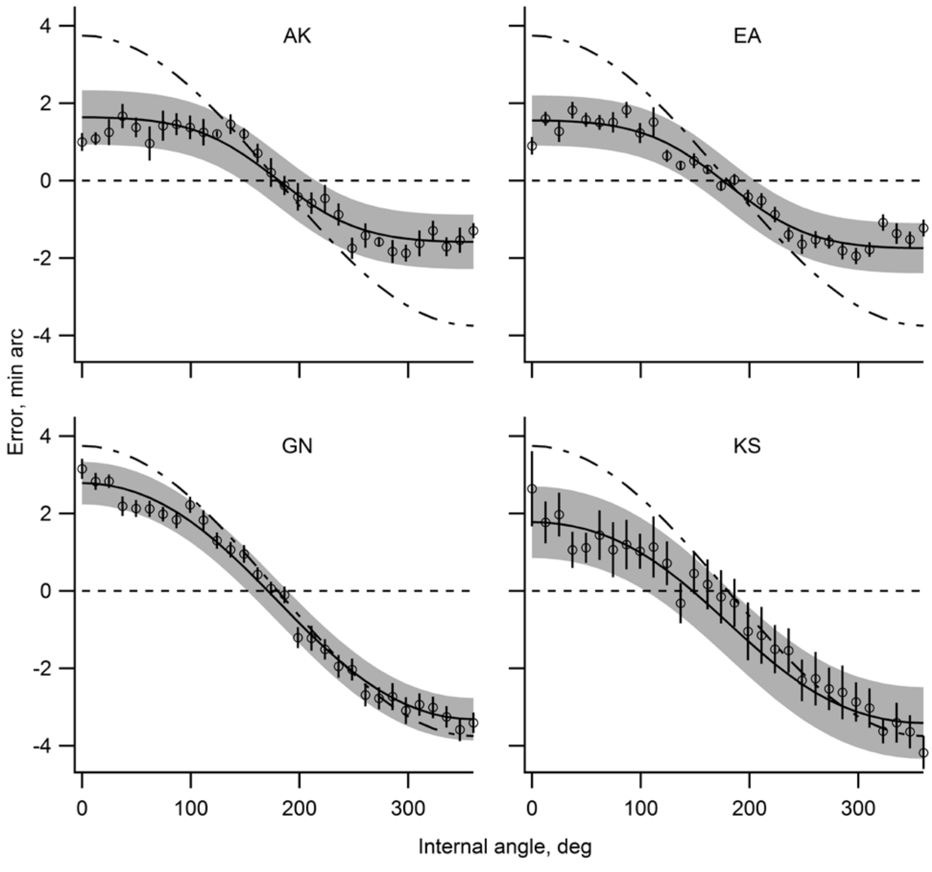


Fig. 4. Illusion of displacement as a function of the internal angle of the wings (α). Four subjects (AK, EA, GN, and KS) tested. Solid curves, and gray bands, the least squares fitting by Formula 1, and confidence intervals for predic ted values, respectively. Dashed-dotted lines – the magnitude of illusion for an infinitely large attentional window. The length (w) and the tilt angle (Φ) of the wings were fixed at 8 min of arc and 0º, respectively; the dimensions of the reference rectangle were 100×63 min of arc. Error bars are ± one standard error of the mean (SEM).

modes of stimulus presentation. We found no significant differences (for the vast majority of the data points, $P>0.05$) between the experimental data obtained for different sizes of the reference rectangle (the last row of Fig. 6).

To check our theoretical predictions, we have fitted the experimental data with Formula 1. A good correspondence between the computational and experimental results was obtained (Fig. 3–6, solid lines); the values of coefficient of determination R^2 in all the cases were higher than 0.9. Analysis of the data with the chi-square test of residuals (df=27, $\alpha=0.05$) confirms this conclusion (Table I). Also, for each calculated curve, the asymptotic variance-covariance matrix of the parameters estimates was calculated by multiplying a matrix of partial derivatives (Jacobian) of the model's function by the residual mean square. These data allowed the examination of the goodness-of-fit by calculating confidence intervals for predicted values at each point along the range of the independent variable (Fig. 3–6, gray bands).

As can be seen in Figures 3–6, the experimental data demonstrate slight systematic shifts (i.e., a lack of strict symmetry) along the ordinate axis. This fact is also reflected in the values of parameter C (Table I) obtained in the curve fitting. Since the bias is observer-specific, we believe that these shifts can be explained by the inherent inaccuracy of the experimental procedure used in the present study (e.g., errors due to the impossibility of having a strict control on the subjects'

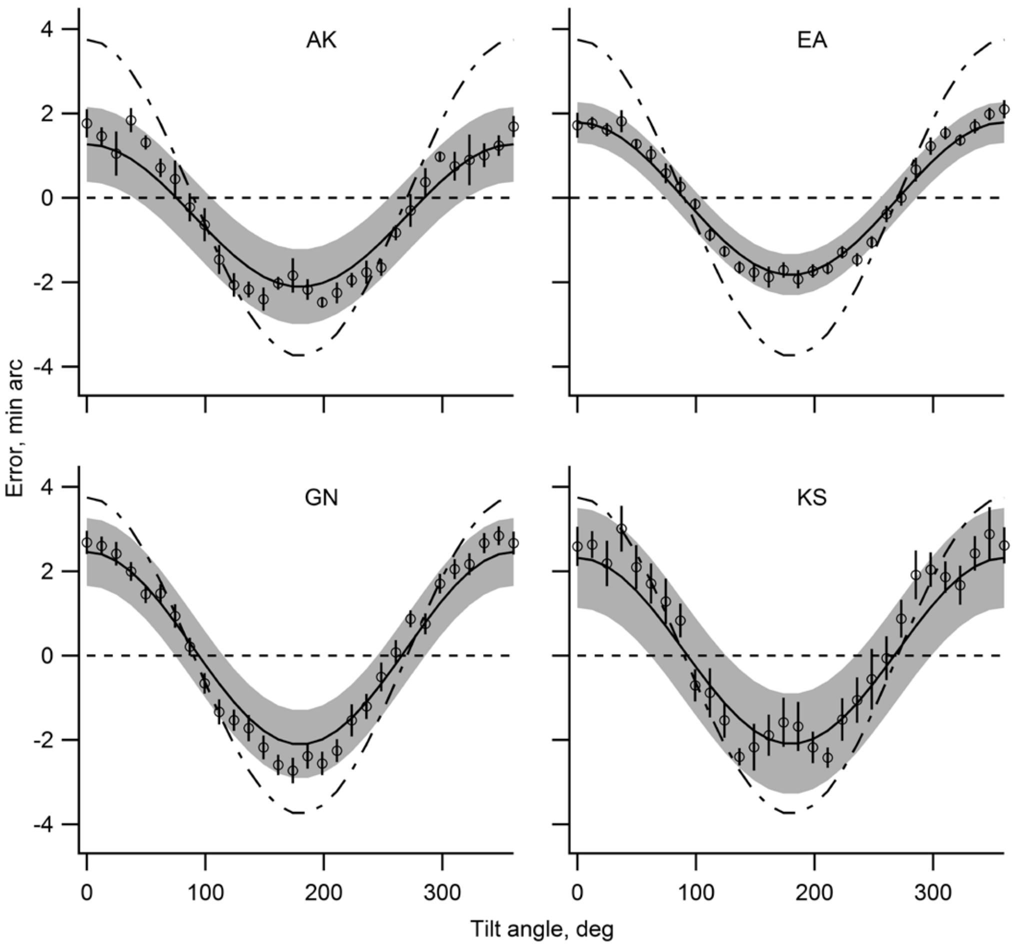


Fig. 5. Illusion of displacement as a function of the tilt angle of the wings (Φ). Four subjects (AK, EA, GN, and KS) tested. Solid curves, and gray bands, the least squares fitting by Formula 1, and confidence intervals for predicted values, respectively. Dashed-dotted lines – the magnitude of illusion for an infinitely large attentional window. The length (w) and the internal angle (α) of the wings were fixed at 8 min of arc and 90º, respectively; the dimensions of the reference rectangle was 100×63 min of arc. Error bars are ± one standard error of the mean (SEM).

Table I

The resulting parameters of fitting Formula 1 to experimental data

Independent variable	Parameters	Subjects			
		AK	EA	GN	KS
Wing length	R^2	0.97	0.96	0.97	0.95
	χ^2	2.822 (ns)	2.754 (ns)	3.967 (ns)	6.545 (ns)
	C	−0.19 ± 0.12	−0.17 ± 0.12	0.49 ± 0.14	−0.01 ± 0.18
	σ	3.95 ± 0.41	3.85 ± 0.38	6.74 ± 1.11	5.13 ± 0.88
Internal angle	R^2	0.94	0.95	0.98	0.95
	χ^2	3.013 (ns)	2.575(ns)	1.811 (ns)	5.181(ns)
	C	0.03 ± 0.12	−0.1 ± 0.11	−0.26 ± 0.1	−0.82 ± 0.16
	σ	3.28 ± 0.34	3.36 ± 0.31	6.13 ± 0.76	4.44 ± 0.66
Tilt angle	R^2	0.93	0.98	0.96	0.92
	χ^2	4.8 (ns)	1.43 (ns)	3.95 (ns)	8.901 (ns)
	C	−0.42 ± 0.16	−0.02 ± 0.09	0.18 ± 0.14	0.11 ± 0.21
	σ	3.54 ± 0.65	3.89 ± 0.39	6.46 ± 2.49	4.88 ± 1.21

(R^2) coefficient of determination; (χ^2) chi-square statistic (ns, $\chi^2<16.151$); (C) (min of arc) a constant component; (σ) (min of arc), determines the width of the circular Gaussian profile of the attentional pooling window

gaze fixation during stimulus observations, or errors caused by biases in judgment and decision-making).

DISCUSSION

The aim of the present study was to check whether substantial systematic positional shifts can emerge in the visual perception of a cluster of separate stimulus terminators and contextual distracters. It also tested whether our theoretical approach, which was previously (Bulatov et al. 2009b, 2010, 2011) applied to explain the emergence of the illusions for full versions of illusory figures (i.e., those comprising three sets of the Müller–Lyer wings representing the Brentano pattern) is relevant for accounting for the data obtained when the task differed from that of length-matching or bisection of spatial intervals. The results of the present experiments demonstrate that the model calculations (based on Formula 1, described in the Methods section) adequately follow the variations of illusion magnitude shown by all the subjects for all three independent variables: the length, internal angle, or the tilt angle of the wings (Figs 3–6, solid lines; Table I). Thus, one can conclude that the results obtained are consistent with the suggestion that the local positional shifts of stimulus terminators can cause the emergence of illusions of extent at least for the stimuli consisting of separate clusters of elements (i.e., having no shaft line). However, for a more reliable assessment of consistency it is necessary to make sure that the displacements of the stimulus terminator obtained in the present study are commensurate with the magnitude of the illusion derived from judgments of extent for full versions of the illusory figures. We believe that for such a comparison the experimental data for flank rotation are most suitable because, in this case, only the amplitudes of the cosinusoidal modulation of illusion magnitude should be considered.

According to the results of our previous study (Bulatov et al. 2011) with stimuli representing the Brentano pattern consisting of three sets of the Müller–Lyer wings and having no shaft line, the tilting of one

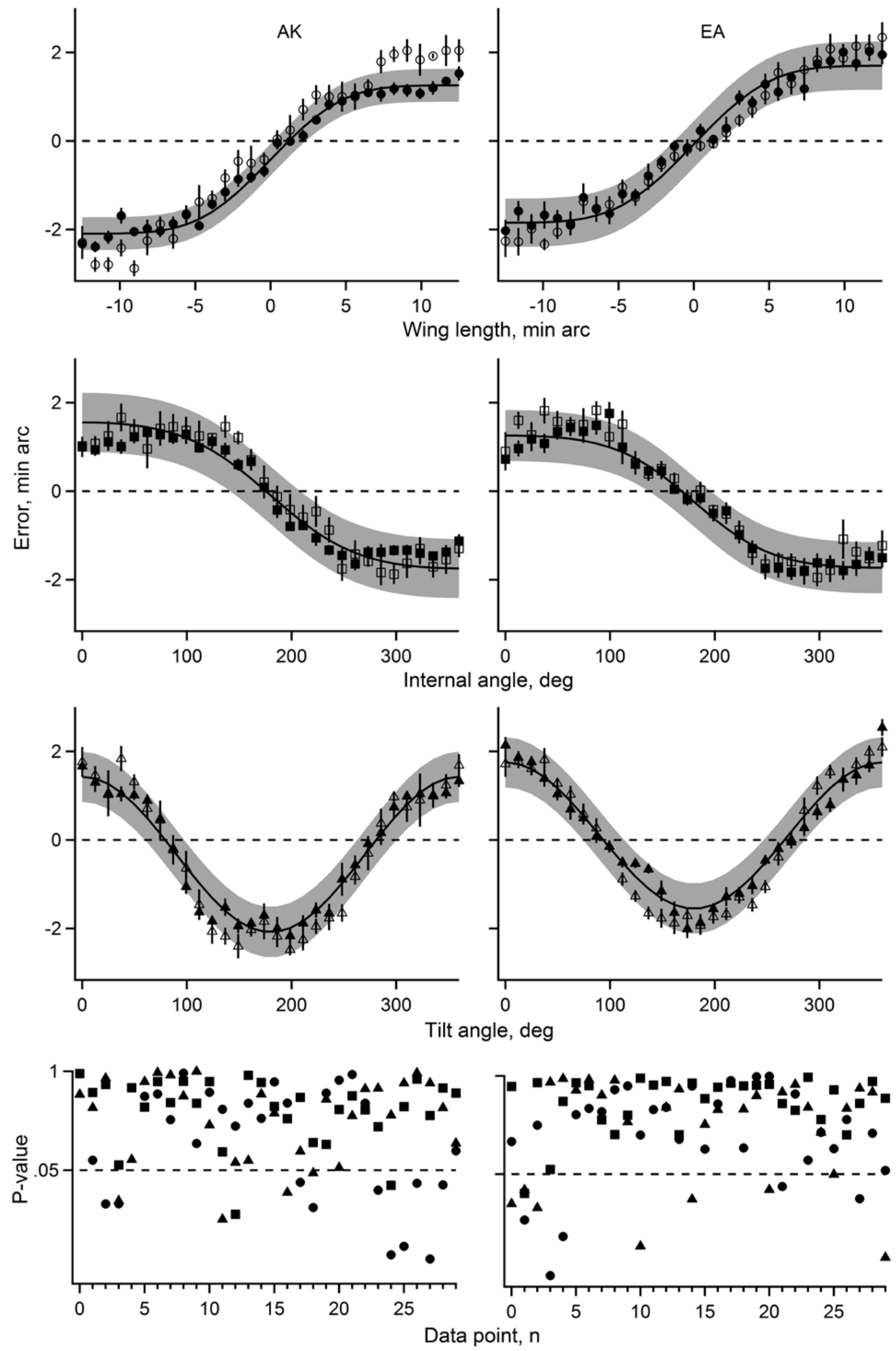


Fig. 6. Evaluation of the influence of the reference rectangle size on the illusion magnitude. Two subjects (AK and EA) tested. Filled and open symbols in the first three rows represent the illusions of displacement as functions of the length (w), the internal angle (α), and the tilt angle (Φ) of the wings for the small (50×63 min of arc) and large (100×63 min of arc) reference rectangles, respectively. Solid curves, and gray bands, the least squares fitting by Formula 1, and confidence intervals for predicted values, respectively (data for the small reference rectangle). Error bars are ± one standard error of the mean (SEM). In the last row, the results of *t*-test (at each data point, *n* along the range of the independent variable) comparisons between the data for the small and large reference rectangles: circles – function of the length; squares – function of the internal angle; triangles – function of the tilt angle of the wings.

of the lateral contextual flanks (the length and the internal angle of the wings were 8 min of arc and 90°, respectively; the length of the stimuli was 120 min of arc) induced the cosinusoidal changes of the illusion magnitude with an amplitude of 2.68 ± 0.27 min of arc (the data averaged over all four observers who participated in the experiments). In turn, the data collected from the four observers in the third series of the present experiments yielded averaged amplitude of 2.17 ± 0.52 min of arc. A comparison with the value from the previous study revealed no significant difference (*t*-test: $t_{6,0.05}$=0.962, *P*=0.232). Consequently, one can conclude that, irrespective of different tasks used in these experiments, the magnitude of perceptual positional shifts of a separate single set of the Müller–Lyer wings is quite compatible with the magnitude of length misjudgments for full versions of these illusory figures.

The fact that the fitting of the data from different series of the present experiments yielded quite similar values for the size of the area of centroid extraction for each observer (parameter σ, Table I) additionally confirms the applicability of the common theoretical interpretation. At the same time, one can suppose that different average sizes of the areas of centroid extraction for different subjects can be explained by their ability to control the parameters of the spot-light of spatial attention (i.e., shrink or expand the attentional window that determines the area of centroid extraction) when performing the experimental task (Olshausen et al. 1993, Han et al. 2005, Theeuwes 2010, Gaspelin et al. 2012). In support of this assumption, some relationship between the subjects' experience and his/her experimental results can be traced: for subjects GN and KS that have participated in psychophysical experiments for the first time, the illusion magnitude tended to approach (but not exceed) the values calculated for the infinitely large attentional windows (Figs 3–5, dashed-dotted lines).

It has been demonstrated in a number of previous studies of illusions of extent (Greene and Nelson 1997, Bulatov et al. 1997, 2005, 2009b, Welch et al. 2004) that illusion magnitude increases proportionally with the lengthening of figures shaft-line (or corresponding empty spatial interval). In the present study, the fact that the illusion magnitude does not depend noticeably on the width of the reference rectangle indicates that some procedures other than those of length-matching or bisection could be used by the visual system in performing the experimental task. Since only the position of the center (and also centroid) of the reference rectangle is independent of its dimensions, one can suppose that the visual system possesses a mechanism which provides extraction and processing of information concerning both the locus of the centroid of the reference rectangle and that of the target (i.e., of stimulus terminator). Therefore, we believe that relatively large areas of centroid extraction (averaged parameter σ for subjects AK: 3.59 ± 0.84, EA: 3.7 ± 0.63, GN: 6.44 ± 2.83, and KS: 4.82 ± 1.64) obtained in the present study can be attributed to the need for observers to deploy spatial attention to both the wings and the reference circles.

The results of our previous experiments with full versions of the Brentano type of illusory figures nor those of the present study with separate Müller–Lyer wings do not allow us to speculate definitely regarding the nature and similarity of higher-level neural mechanisms involved in performing such different visual tasks – comparisons of the extent of stimulus parts and the assessment of positional displacements of a single set of wings. However, the success in the application of the same computational approach in explanation of different experimental data strongly supports the suggestion that the observers' misjudgments in both studies were determined by the same factor, i.e., by the weighted averaging of the positional signals (centroid extraction) which provides necessarily low spatial resolution for the neural mechanism of assessment of the relative location of the visual objects. In a biological sense, the advantage of such a mechanism is that it enables fast and reliable perception of the position of objects, regardless of their size, shape, and illumination within a dynamically changing environment.

CONCLUSIONS

The psychophysical examinations of a single set of the Müller–Lyer wings were performed. It was demonstrated that the magnitude of perceptual displacements of the stimulus terminator obtained in present experiments is commensurate with that of the illusion derived from judgments of extent in our previous studies of full versions of the illusory figures. Good correspondence between the experimental results and the predictions of our computational model of automatic centroid extraction provides strong support for the suggestion that, at least for the stimuli consisting of separate clusters of elements, the effects of centroid extraction are powerful enough to be considered as one of the main causes of illusions of extent of the Müller–Lyer type.

REFERENCES

Akutsu H, McGraw PV, Levi DM (1999) Alignment of separated patches: multiple location tags. Vision Res 39: 789–801.

Badcock DR, Hess RF, Dobbins K (1996) Localization of element clusters: Multiple cues. Vision Res 36: 1467–1472.

Bulatov A, Bertulis A (2005) Distracting effect in length matching. Acta Neurobiol Exp (Wars) 65: 265–269.

Bulatov A, Bertulis A, Bielevicius A, Loginovich Y (2009a) Distracter influence on the right angle perception (in Russian). Zhurnal Vysshei Nervnoi Deiatelnosti Imeni I P Pavlova 59: 259–268.

Bulatov A, Bertulis A, Bulatova N, Loginovich, Y (2009b) Centroid extraction and illusions of extent with different contextual flanks. Acta Neurobiol Exp (Wars) 69: 504–525.

Bulatov A, Bertulis A, Gutauskas A, Mickiene L, Kadziene G (2010) Center-of-mass alterations and visual illusions of extent. Biol Cybern 102: 475–487.

Bulatov A, Bertulis A, Mickiene L (1997) Geometrical illusions: study and modelling. Biol Cybern 77: 395–406.

Bulatov A, Bertulis A, Mickienė L, Surkys T, Bielevičius A (2011) Contextual flanks' tilting and magnitude of illusion of extent. Vision Res 51: 58–64.

Bulatov A, Bulatova N, Surkys T (2012) Perpendicularity misjudgments caused by contextual stimulus elements. Vision Res 71: 1–9.

Gaspelin N, Ruthruff E, Lien MC, Jung K (2012) Breaking through the attentional window: Capture by abrupt onsets versus color singletons. Atten Percept Psychophys 74: 1461-1474.

Greist-Bousquet S, Schiffman HR (1981) The role of structural components in the Mueller-Lyer illusion. Percept Psychophys 30: 505–511.

Greene E, Nelson B (1997) Evaluating Müller-Lyer effects using single fin-set configurations. Percept Psychophys 59: 293–312.

Han S, Jiang Y, Mao L, Humphreys GW, Qin J (2005) Attentional modulation of perceptual grouping in human visual cortex: ERP studies. Human Brain Mapping 26: 199–209.

Hirsch J, Mjolsness E (1992) A center-of-mass computation describes the precision of random dot displacement discrimination. Vision Res 32: 335–346.

McGraw PV, Whitaker D, Badcock DR, Skillen J (2003) Neither here nor there: localizing conflicting visual attributes. J Vision 3: 265–273.

Morgan MJ (1999) The Poggendorf illusion: a bias in the estimation of the orientation of virtual lines by second-stage filters. Vision Res 39: 2361–2380.

Morgan MJ (2010) Features and "primal sketch". Vision Res 51: 738–753.

Morgan MJ, Glennerster A (1991) Efficiency of locating centers of dot-clusters by human observers. Vision Res 31: 2075–2083.

Morgan MJ, Hole GJ, Glennerster A (1990) Biases and sensitivities in geometrical illusions. Vision Res 30: 1793–1810.

Morgan MJ, Ward RM, Cleary RF (1994) Motion displacement thresholds for compound stimuli predicted by the displacement of centroids. Vision Res 34: 747–749.

Olshausen BA, Anderson CH, Van Essen CD (1993) A neurobiological model of visual attention and invariant pattern recognition based on dynamic routing of information. J Neurosci 13: 4700–4719.

Post RB, Welch RB, Caufield K (1998) Relative spatial expansion and contraction within the Müller-Lyer and Judd illusions. Perception 27: 827–838.

Predebon J (2001) Spatial range of illusory effects in Müller-Lyer figures. Psychol Res 65: 226–234.

Predebon J (2005) A comparison of length-matching and length-fractionation measures of Müller-Lyer distortions. Percept Psychophys 67: 264–273.

Searleman A, Porac C, Dafoe C, Hetzel B (2005) Altering Mueller–Lyer illusion magnitude using figural additions at the wing–shaft intersections. Am J Psychol 118: 619–637.

Searleman A, Porac C, Alvin J, Peaslee K (2009) Manipulating the strength of the Ponzo and horizontal–vertical illusions through extraction of local cue information. Am J Psychol 122: 383–394.

Theeuwes J (2010) Top-down and bottom-up control of visual selection. Acta Psychol 135: 77–99.

Ward R, Casco C, Watt RJ (1985) The location of noisy visual stimuli. Can J Psychol 39: 387–399.

Watt RJ, Morgan MJ (1983) The recognition and representation of edge blur: Evidence for spatial primitives in vision. Vision Res 23: 1465–1477.

Welch RB, Post RB, Lum W, Prinzmetal W (2004) The relationship between perceived length and egocentric location in Muller-Lyer figures with one versus two chevrons. Percept Psychophys 66: 1095–1104.

Westheimer G, McKee SP (1977) Integration regions for visual hyperacuity. Vision Res 17: 89−93.

Whitaker D, Walker H (1988) Centroid evaluation in the vernier alignment of random dot clusters. Vision Res 28: 777–784.

Whitaker D, McGraw PV, Pacey I, Barrett BT (1996) Centroid analysis predicts visual localization of first- and second-order stimuli. Vision Res 36: 2957–2970.

Wright JM, Morris AP, Krekelberg B (2011) Weighted integration of visual position information. J Vision 11: 1–16.

Zanker JM, Abdullah AK (2004) Are size illusions in simple line drawings affected by shading? Perception 33: 1475−1482.