Perception, 1999, volume 28, pages 949–964

DOI:10.1068/p2889

Characterisation of the misalignment and misangulation components in the Poggendorff and corner-Poggendorff illusions

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Received 20 January 1999, in revised form 2 June 1999

Abstract. In the Poggendorff illusion, two colinear segments abutting obliquely on an intervening configuration (often consisting of two long parallel lines) appear misaligned. We report here the results of a component analysis of the illusion and several of its variants, including in particular the 'corner-Poggendorff' illusion, and variants with a single arm. Using a nulling method, we determined an 'orientation profile' of each configuration, that is, how the illusions varied as the configuration was rotated in the plane of the display. We were able to characterise a pure-misalignment component (having peaks and dips around the $\pm 22.5°$ and $\pm 67.5°$ orientations of the arms) and a pure misangulation component of constant sign, having peaks at the $\pm 45°$ orientations of the arms. Both these components were present in both the classic and the corner-Poggendorff configurations. Thus, the misangulation component appears clearly in the classic Poggendorff illusion, once the misalignment component is partitioned out. Similarly, the corner-Poggendorff configuration, which essentially estimates a misangulation component, contains a misalignment component which becomes apparent once the misangulation is nulled. While our analysis accounts for much of the variability in the shapes of the profiles, additional assumptions must be made to explain the relatively small misangulation measured in the corner-Poggendorff configuration (1.5°, on average, at peak value), and the relatively large illusion measured in the configurations with a single arm (above 6°, on average, at peak values). We invoke the notion that parallelism and colinearity detectors provide counteracting cues, the first class reducing misangulation in the corner-Poggendorff configuration, and the second class reducing the illusion in the Poggendorff configurations with two arms.

1 Introduction

In the Poggendorff illusion, there are two colinear segments abutting obliquely on two, usually long, parallel lines (figures 1e and 1f). More generally, one classifies with the Poggendorff illusion all figures containing an internal, elongated shape, which we will call the body, or the intervening configuration, and two colinear elements—whole segments, dashed lines, or aligned dots—which we will call the arms. The illusion consists in the fact that the two arms appear to be parallel but not colinear, and the direction of their lateral separation is what would have occurred had the segments rotated around their intersections with the parallel lines so as to abut there more orthogonally. This way of describing the perceptual effect in the illusion amounts to saying that the illusion consists in an error of angle: a 'misangulation'. Such a tendency for acute angles to be judged as being closer to right angles has been suggested by Hering, Helmholtz, Wundt, and others as underlying many illusions (review in Robinson 1972).

An alternative way of describing the perceptual effect in the Poggendorff illusion is to say that it is not that the angles have changed, but that the line segments have undergone a shear, or shift parallel to themselves, along the long lines forming the body of the figure (Goldstein and Weintraub 1972; Day 1973).

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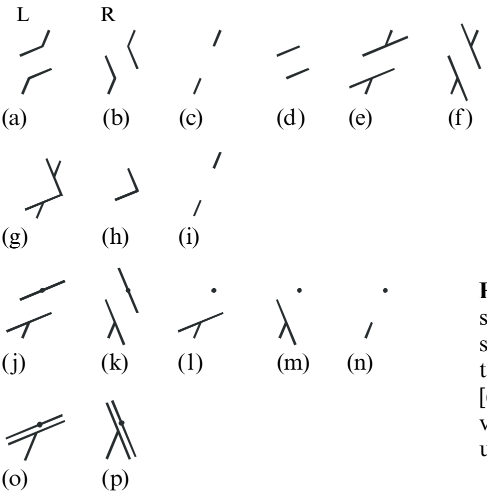

Figure 1. Configurations used in the first [(a) – (f)], second [(g) – (i)], and third [(j) – (n)] experimental series. Control configurations (c) and (i) are identical. The configurations are shown in both their L [(a), (e), (j), (l), (o)] and R [(b), (f), (k), (m), (p)] versions. Configurations (o) and (p) are the ones used by Weintraub et al (1980).

Although most authors admit that the Poggendorff illusion is a compound illusion, involving at least two, and perhaps as many as five, components (eg Day and Dickinson 1976; Hotopf and Hibberd 1989; Morgan 1996), one important, unsolved question is whether the loss of colinearity is due to misalignment or misangulation. Unfortunately in the normal Poggendorff configuration these two types of change cannot be distinguished by a nulling method because they have the same end effect of giving rise to noncolinearity of the arms. Attempts have been made, in several experimental studies, to correlate the Poggendorff effect with some possibly related effect, which, by design, could generate only one type of change. For instance, if the separation between the two long lines forming the body is underestimated ('parallel-attraction effect'), the colinear segments, being perceived closer than they are, would also be seen misaligned (Finlay and Caelli 1975). If the acute or obtuse angles in the configurations induce contractions or expansions of the body lines, as expected in the Müller-Lyer illusions, again, a misalignment would result in the usual direction (Greist-Bousquet and Schiffman 1985). On the other hand, a physiological mechanism based on neural blur in circular filters (Morgan and Casco 1990), in which acute angles at the intersection points are not sufficiently well differentiated from right angles, leads naturally to a description in terms of misangulations. Note, however, that a Poggendorff-like illusion is obtained with obtuse angles (Wenderoth et al 1978) and even with right angles (Gillam 1971).

A way of detecting whether misangulation occurs would be to add a reference line to the figure in order to determine whether a change in orientation of the arms has occurred (Hotopf and Ollerearnshaw 1972). However, adding a reference line alters the global figure, and interactions with the figure might occur which would cause the orientation of the reference line itself to be misjudged.

The 'corner-Poggendorff' illusion described by Greene (1988) is a variant of the Poggendorff configuration in which the intervening parallels are replaced by two lines forming a corner (figure 1g). The advantage of this configuration is that, contrary to the case of the classic Poggendorff, misangulation and misalignment can be separated. This is because the misangulation component, instead of causing an apparent error of colinearity as it did in the classic Poggendorff, now causes a difference in relative orientation of the two arms. Such a difference in orientation is indeed subjectively observed, suggesting the existence of a misangulation component also in the classic Poggendorff illusion. On the other hand one could argue that what is seen in this variant has nothing to do with the Poggendorff illusion (Vicario and Zambianchi 1993) and must be classified with an illusion studied by Judd (1899) in which two colinear arms, abutting on an ellipse, appear to have slightly different orientations. Nevertheless, if both the corner-Poggendorff and the standard Poggendorff are multicomponent illusions it is clear that although there may be dissimilar aspects, the illusions may nevertheless share some components. Certainly it is clear that a large portion of the noncolinearity that is measured in the classic Poggendorff illusion (and many variants) is dominated by a 'pure'-misalignment effect, that is, an effect measured even in the absence of the intervening body of the configuration. In particular, according to Day et al (1977), most of the effect observed when the body is delimited by subjective contours (Gregory 1972) would be due to pure misalignment. What we wish to show here is that once the pure-misalignment effect is subtracted from the effect measured in the complete configuration, there is a residual signal, which we are able to measure accurately. We will show that this residual signal agrees with the misangulation component of the corner Poggendorff, thus strengthening—against current conceptions—the case for the relatedness between the standard and the corner-Poggendorff illusions.

In many illusory figures, the illusory effect is maximum when the long axis of the figure is oriented along the $\pm 45°$ obliques (eg Oyama 1960). Beyond this general trend, each illusion, we believe, presents characteristic features which we wish to determine with precision, in order to clarify the relationships between various illusions. In this technique, the sign and strength of an illusion are measured as it is rotated to all possible orientations in the plane of the paper. This gives a 'signature' which we call the 'orientation profile' of the illusion. Comparison of the orientation profiles of variants of an illusion gives an indication of their relatedness.

In the context of the Poggendorff illusion, Weintraub et al (1980) studied the variants shown in figures 1o and 1p, with two parallels and a single arm which had to be aligned with a point. The orientation profiles were determined at twelve different orientations of both the left and the right variants, and six different values of the angle between the arm (which they name transversal) and the parallels. They established that the positions of the maxima, while subject to small shifts depending on the abutting angle, were dominated by the orientation of the arms. Orientation profiles have also been used to study the Zöllner illusion (Ninio and O'Regan 1996), and show that the illusion is, in essence, present even when a single 'stack' of segments is displayed. In the present paper we report on the orientation profiles in the standard and corner-Poggendorff illusions and some of their variants and show how these profiles answer the question of their relatedness.

2 Materials and methods

2.1 *General*

We used experimental procedures similar to those used in our work with the Zöllner illusion (Ninio and O'Regan 1996). In particular, the illusions were measured by a nulling procedure, ie changing a configuration until a perceived deviation (eg from colinearity or from squareness) was cancelled. Each variant was presented at a number of orientations in the plane of the display, so as to obtain an 'orientation profile'.

Although our methodology agrees with current practice, one should be reminded that 'perception on a monitor screen' is not necessarily ecologically valid (eg Hurlbert 1998). In natural settings, patterns are often seen on slanted planes, while in the laboratory the figures are nearly always viewed frontally—with, however, a few fortunate exceptions (eg Horrell 1971). Two decades ago, laboratory experiments were often conducted in the dark, with very small stimuli (less than a degree of apparent size), and the subject's head was immobilised on a chin-rest. In our studies we operate in the light, and the subjects move their eyes freely (but were instructed not to tilt their heads in an attempt to compensate for the orientation changes in the figure). Information about horizontal and vertical axes is provided by the environment and, in particular, by the rectangular frame of the screen. This may of course exert an influence on the horizontal–vertical anisotropies. In this respect we note that our measurements for the horizontal – vertical anisotropy on a letter L-shaped configuration are rather small (from near 0% to somewhat less than 1%) while the values obtained with earlier techniques were in the 1% – 10% range (eg Finger and Spelt 1947; Künnapas 1959). Last, one might consider inscribing the figures within a disc, in order to create a more isotropic environment, but we considered that a figure within a disc within a rectangle was not necessarily more ecologically valid than the same figure directly within the rectangle. Furthermore, Künnapas (1959), comparing viewing the letter L – shaped illusion with a circular versus a horizontally oblong visual field (similar to a computer monitor) found nearly identical values of the illusion (3.7% versus 4.1%). In any event, the main motivation of our work was to compare the orientation profiles of various illusions under a same set of conditions, since we were more interested here in exploiting the relationships between profiles than in establishing their ecological validity.

2.2 *Stimuli*

The configurations consisted in three groups of figures: in the first group (figures 1a – 1f) there were two variants of the classic Poggendorff configuration and two control configurations associated with them, a pure-alignment control (figure 1c), known as the Zehender illusion (Zehender 1899) and two controls of the perceived squareness of the basic configuration (figures 1a, 1b, and 1d). In the second group of figures (figures 1g – 1i) there were the corner-Poggendorff configuration and two controls associated with it. In the third group there were Poggendorff variants with just one arm (figures 1j – 1m) and their associated control (figure 1n). The first variant (figures 1j and 1k) is derived from the configuration studied by Weintraub et al (1980) (figures 1o and 1p). The associated control (figure 1n) was discussed by Bouma and Andriessen (1968).

All the configurations were constructed around a central (virtual, invisible) rectangle shown as dotted lines in figure 2. When arms were present in the configuration, they were angled at 135° to the edges of the virtual rectangle. In all the configurations, 'correct'

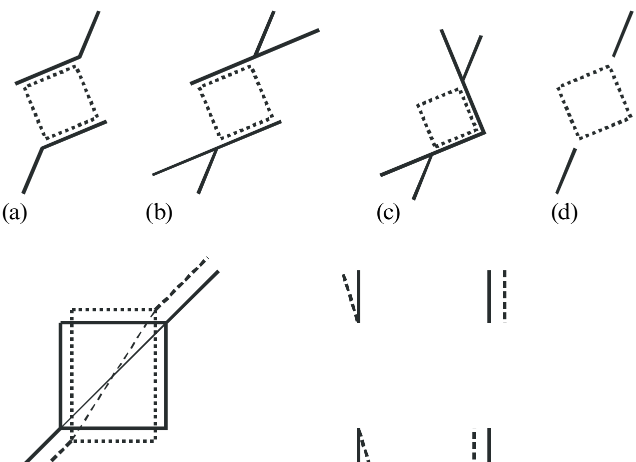

Figure 2. Conventions and definitions. All the configurations were constructed around a central (virtual, invisible) rectangle, shown as dotted. The figures were adjusted by changing the ratio of the sides of the rectangle. Correct adjustment corresponds to the equality of the sides (a) – (d) so that the rectangle becomes a square, as shown. The magnitude of the illusion is calculated as shown in (e). The dashed line corresponds to the setting made by the subject. From the ratio of the sides of the rectangle, the angle between the real and the adjusted diagonals is computed and used as a measure of the illusion. The sign of the pure-misalignment illusion is positive when the arms are perceived as indicated with the dashed lines in (f) or (g).

alignment of the arms occurred when the virtual rectangle was a square. The lengths of the arms were equal to half the diagonal of the square.

Figures 1e and 1f show the configurations resembling the classic Poggendorff configuration. Figures 1a and 1b are obtuse-angle versions of these figures in which the internal body was derived from a square. There was additionally a 'make-square' configuration (figure 1d), and figures 1a and 1b were also used for 'make-square' adjustments.

Each configuration could occur in two versions, which we call the L and R versions, according to its handedness. We chose to define as 'L' the configurations shown in figures 1a, 1e, 1j, 1l, and 1o. This particular choice is consistent with our definition of handedness in the case of the Zöllner illusion (Ninio and O'Regan 1996). Indeed, the classical Poggendorff configuration shown in figure 1e has the L configuration, as defined here, and it also has the L configuration when it is considered as a Zöllner pattern (with the two arms replaced by a continuous line). In the case of symmetrical configurations (1c, 1d, 1i, and 1n), L and R versions are confounded. In the corner-Poggendorff group (figures 1g and 1h), we can define a 'left side' and a 'right side' of the corner. By convention here, the left and right sides are defined as seen when the corner is oriented like the letter V.

In the first series (figures 1a – 1f), independently of whether the task involved making the arms look colinear or making the body of the figure look square, the way the change occurred was always the same: the computer adjusted the relative lengths of the sides of the (virtual) rectangle that formed the central body of the configuration, shown as dotted lines in figures 2a – 2d. The adjustment was made so that the sum of the sides of the rectangle remained constant, and only their ratio changed. This way of making the adjustment also applied to the pure alignment configuration (figures 1c and 1i), even though here none of the segments of the internal virtual rectangle was actually visible. All the configurations were such that when their arms were correctly aligned, the virtual rectangle was a square. The net effect of the mode of adjustment effectively consisted in a motion of the arms parallel to themselves.

In the corner-Poggendorff variant (figure 1g), the observer's adjustment was done in two stages: a first adjustment required the arms to be made to look parallel. For this, the angles that both arms made with the body part of the figure were simultaneously increased or decreased by the same amount. After this adjustment, and with the angles of the arms maintained as they had been adjusted, a second type of adjustment then required observers to align the arms so they looked colinear. As in the normal Poggendorff configurations, this second adjustment was made by changing the ratio of the sides of the virtual rectangle formed by the body of the configuration.

The third experimental series (figures 1j – 1n) used configurations which were also constructed on a virtual square. Adjustment was made by rotating the arm around its centrally located endpoint until the arm looked colinear with the isolated point. It should be noted that in the work of Weintraub et al (1980), using the configurations of figures 1o and 1p, the adjustment was done in a different way, namely by moving the point, rather than by rotating the arm.

In all cases, the figures were presented to subjects in orientations ranging from 0° to 337.5° in steps of 22.5°.

2.3 *Sign and magnitude conventions*

Our primary experimental measurement consists in the ratio of the lengths of the sides of the virtual rectangle, as they are found after the subject has made his or her adjustment. Departure from the 1 : 1 ratio signals an illusion. Here, we measure the illusion by an angle α which indicates how the orientation of a diagonal is changed when going from the square to the rectangle (figure 2e). An angle of 1° obtains with a 1.0088 : 1.000 rectangle. This angle can characterise metric distortions (errors of width-to-length ratio), misangulations, or misalignments. With the Poggendorff figures 1a, 1b, 1e, and 1f, if the illusion is due to a pure misangulation by an equal angle for the two arms, this angle is given by α, as measured in the nulling procedure. If the illusion is interpreted as a misalignment, involving a sliding of the abutting points along the parallel sides, this misalignment can also be described by the angle α. Misangulation in the corner Poggendorff was measured as the deviation of the arms from the 45° angle of the correctly aligned figure.

In all Poggendorff figures and their variants, including the variants with a single arm and the corner-Poggendorff variants, the illusion is counted positively when it can be simulated by a misangulation towards orthogonality. Note that when the body contains two internal parallel lines, a 'parallel-attraction effect' would give the same sign convention.

In the 'pure-misalignment' controls (figures 1c and 1i) one does not know whether the measured misalignment is due to a relative sliding of the two lines (shear) or to a simultaneous clockwise or counterclockwise rotation of the two lines. In case of a rotation around the proximal endpoints, the rotation angle β would correspond to a misangulation in a Poggendorff figure. Our sign convention is as follows: a positive-misalignment illusion corresponds to a perception of segments that are rotated counterclockwise with respect to their endpoints (figure 2f). A different, equally general definition can be given without using rotations. Consider two aligned segments a and b. Orienting ourselves along the direction from a to b, the illusion is positive when b is perceived as being shifted to the right with respect to a (figure 2g).

In terms of regressions to the horizontal or the vertical directions, consider the case in which the regression is achieved through rotations of the segments around their midpoints. Then, regression to the horizontal or the vertical would be counted as positive or negative according to whether the oblique segments are ascending or descending. For an ascending oblique (ie from bottom left to top right) close to the horizontal, a regression to the horizontal gives a negative sign. For a descending oblique, a regression to the horizontal gives a positive sign. In the case of obliques that are close to the vertical direction, a regression to the vertical would give a positive sign with the ascending oblique, and a negative one with the descending oblique.

With the chosen sign convention, if the two colinear lines are completed so as to form an 'L' Poggendorff figure, a positive-misalignment illusion corresponds to a positive Poggendorff effect. In this way, if misalignment is a component of a Poggendorff illusion, a positive misalignment contributes positively to the L version and negatively to the R version.

In the 'make-square' tests associated with figures 1a, 1b, and 1d, a positive sign always corresponds to a parallel-attraction effect. In the 'make-square' test associated with the corner-Poggendorff figure (figure 1h), a positive sign corresponds to an overestimation of the left side of the corner (seen as a 'V'). With this convention, a positive 'make-square' illusion corresponds to a positive-misalignment effect in the complete corner-Poggendorff figure.

2.4 *Subjects*

Ten subjects, including the two authors, participated in the first two experimental series. Six of these subjects, including the two authors, participated in the third experimental series.

2.5 *Procedures*

The stimuli were presented on the 19-inch monitor of a Silicon Graphics IRIS workstation. Subjects sat at a comfortable distance (about 60 cm) from the screen. The figures, in black, were presented in the centre of a 34 cm × 25 cm light-grey area. The virtual square of the figures was 2.75 cm in length (about 100 pixels), and subtended an angle of 2.6 deg.

There were three experiments. The first involved standard and obtuse-angle Poggendorff configurations and their controls (figures 1a – 1f), the second involved the corner Poggendorff and its controls (figure 1g – 1i), and the third involved Poggendorff variants with one arm and the associated control (figures 1j – 1n). Within each experiment, the various configurations were shown in a fixed order. It was 1a, 1b, 1c (align), 1d, 1a, 1b (make square), 1e, 1f (align) in the first experiment, 1i (align), 1h (make square), 1g (make parallel, then align) in the second, and 1j, 1k, 1l, 1m, 1n (align) in the third. For each variant, the orientations were given in a random order, which was varied with each subject, and on each repetition of the experiment. Each subject ran the first experiment ten times, then the second experiment ten times, and six subjects then ran the third experiment ten times.

The subject adjusted the shape of the configuration by pressing on the left or right mouse button. At each press, the figure changed in such a way that the lengths of the sides of the virtual internal rectangle on which the figure was built increased or decreased by steps of 1/80th of the length of the side of the virtual square. When subjects were satisfied with their adjustment, they clicked twice on the central mouse button, and the next orientation or the next variant was presented. In each trial, the virtual rectangle was initially set at eight adjustment steps from the square configuration, the direction of the initial deviation being chosen at random.

3 Results

3.1 *Make-square component*

Figure 3 shows the results for the three controls (figures 1a, 1b, 1d, and 1h) for which the task was to make the inner configuration look square. The a priori expectations are that the results should reflect (1) the horizontal – vertical anisotropy (ie vertical extents should be overestimated) and (2) the attraction-of-parallels effect (ie for configurations 1a, 1b, and 1d, the materialised sides of the squares should appear larger than those that are not represented).

In the case of figure 1d (two parallel sides of a square) the L and R versions are identical: the difference in the two halves of the experiments for this configuration gives a measure of the variability in our measurements (open and closed symbols in figure 3a). The results show good symmetry with respect to the vertical axis (figure 3a). The illusion oscillates around an average positive value of about 0.3°. The maxima and minima agree with the classical vertical – horizontal effect (vertical extents are overestimated with respect to horizontal ones), and this effect would contribute about $\pm 0.7^\circ$ in the horizontal and vertical directions. In the case of the more complex configuration of figures 1a and 1b, the results, shown in figure 3b, are roughly similar in profile, and slightly shifted upwards, indicating a small influence of the arms on the perceived separation of the parallels (see also Finlay and Caelli 1975). There might be some differences between the L and R configurations, but these are not clear enough to deserve further comments.

In the case of figure 1h, two sides of a corner are compared. By convention here, the illusion is counted positive when the left side of the 'V' is overestimated. Since the illusion is more often positive than negative (figure 3c) there is a slight left-side-overestimation effect (average value: 0.08°). There is no significant horizontal – vertical effect in this data set.

3.2 *Pure-misalignment tasks*

Figure 4a shows the strength of the effect measured in the pure-misalignment task associated with the Poggendorff configuration (figure 1c), and figure 4b that associated with the corner Poggendorff (figure 1i). There are four independent data sets, which show good consistency. The illusion is slightly reduced in the second data set, presumably owing to the effect of practice. The absolute value of the pure-misalignment component

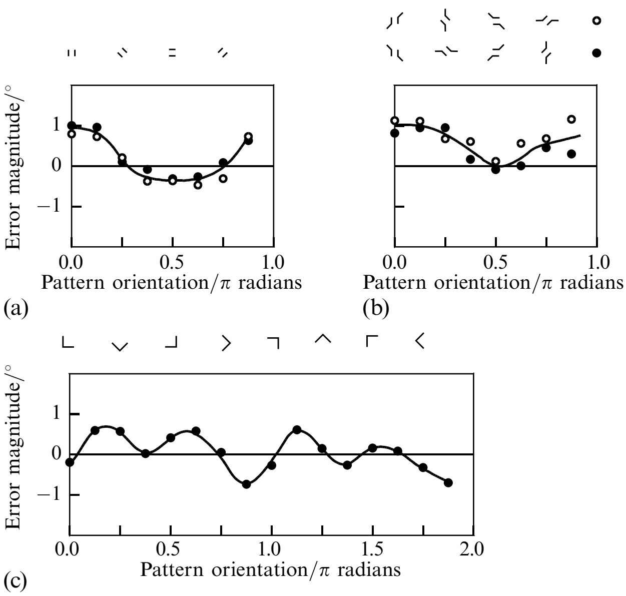

Figure 3. 'Make-square' tasks. As in all subsequent figures, the icons above the displays show the configuration on which the task was performed. In this and subsequent graphs, the abscissa corresponds to orientations in multiples of π radians. One π radian corresponds to half a turn, or 180°. An error of 1° corresponds to an overestimation or underestimation of the ratio of the sides by 0.9%. The interval between the data points is 0.125π radians, that is 22.5°. In (a) and (b), a positive error corresponds to a situation in which the separation of the parallel sides is underestimated with respect to their length. The shape of the curve seems dominated by the traditional vertical–horizontal effect. In (c), a positive error corresponds to an overestimation of the left side of the 'V'. Each data point is an average over one hundred measurements (ten measurements made by each of ten subjects). The black discs and the unfilled circles in (a) represent independent measurements made as controls with respect to the L and R Poggendorff configurations shown in (b).

is maximum at ±22.5° off the horizontal. There are less pronounced maxima at ±22.5° off the vertical. The profile is clearly distinguishable from the 'make-square' profiles in figures 3a and 3b.

The sign of the illusion for the ascending or descending obliques close to the horizontal or vertical directions agrees with a regression to the horizontal or vertical directions respectively. However, a reduced misalignment effect is also observed at the horizontal and vertical orientations, which cannot be rationalised by the regression rules. With vertical segments the upper one was misjudged to the right, and with a pair of horizontal segments the one on the left was misjudged to be higher. Presumably these effects are absent in Vernier-acuity measurements, because there the separation of the segments is very small, while in our study it is twice as large as the length of the segments, or about 4 deg.

3.3 *Misalignment within the corner-Poggendorff configuration*

This misalignment is measured after the two arms have been adjusted to look parallel. The curve is not easy to interpret, but it could be said that the orientation profile (figure 4c) resembles both the pure-misalignment profiles of figures 4a and 4b and the make-square profile for a corner configuration (figure 3c). In particular, the negative peak towards orientation 0.875π radians (descending oblique at −22.5° to the vertical) seems to attest to the influence, around this orientation, of the metric (make-square) judgment over the alignment task.

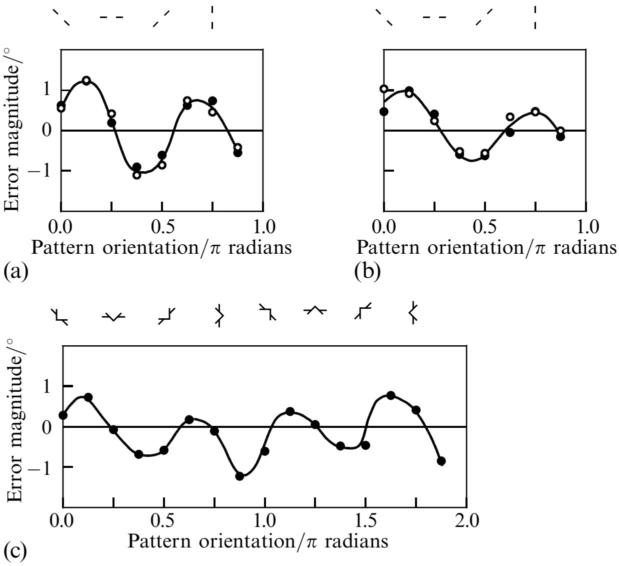

Figure 4. Alignment tasks. A positive sign corresponds to an error in the direction of a counterclockwise rotation of the two segments around their proximal endpoints (as in figure 2f). The results in (a) and (b) correspond to the alignment controls included in the first (figure 1c, in set 1a – 1f) and second (figure 1i, in set 1g – 1i) experimental sets, respectively. The empty and filled symbols correspond to data deriving from test blocks done with L and R Poggendorff configurations. (c) Shows the results of the misalignment task performed on a corner-Poggendorff configuration, after the arms had been rotated to look parallel (nulling of the misangulation illusion). Each point represents an average over one hundred measurements (ten measurements × ten subjects).

3.4 *Pointing task*

The 'pointing error' in the configuration of figure 1n (misalignment of a segment with a point) was designed as a control for the tests on configurations in figures 1j – 1m. Adjustment here, as in the other tests of this series, is made by rotating the segment with respect to its endpoint that is proximal to the isolated point. The results (figure 5),

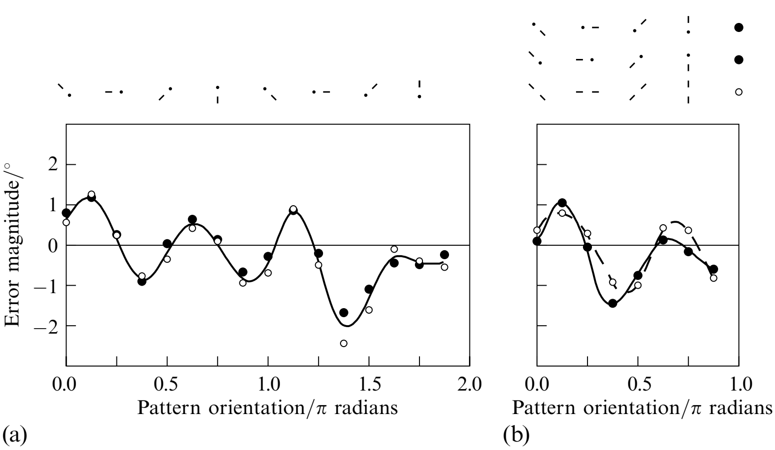

Figure 5. Pointing task. The sign convention is the same as for figure 4. In (a) two independent sets of results are shown that were obtained as controls with respect to the L and R configurations in figure 8. Each point is an average over ten adjustments made by each of six subjects. In (b), each data point indicated by a black disc corresponds to the mean of two corresponding configurations shown above the figure. (b) shows that the results obtained by the same subjects in the pure-misalignment task (figure 1c) agree with those on the pointing task.

for the subset of six subjects who performed this series, are in good agreement with their results on the pure-misalignment task (figure 4).

3.5 *Standard and obtuse-angle Poggendorff configurations*

The results are shown separately for the L and R configurations (figure 6). Contrary to the preceding controls, the illusion is now always positive (by definition, in agreement with a regression to orthogonality), and it is systematically stronger with the standard than with the obtuse-angle Poggendorff configurations. The peaks and troughs are located at the same orientations as in the pure-misalignment effect plotted in figure 4 (remember that in the case of the R configuration the sign of the associated misalignment control must be reversed). The peak-to-trough variations are more pronounced with the R configurations.

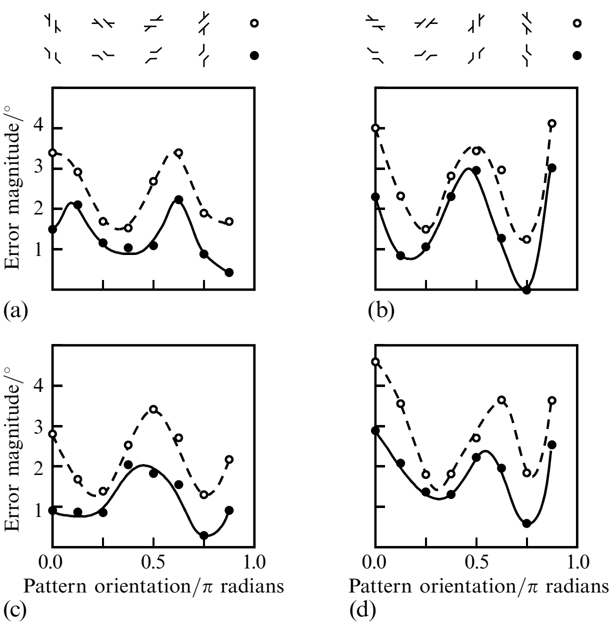

Figure 6. Misalignment measured in the obtuse-angle and standard Poggendorff configurations. The results for the L and R configurations are shown separately, in the left and right panels respectively. The primary results are shown in (a) and (b). The results after subtraction of the pure-misalignment effect (figure 4a) are shown in (c) and (d). Note that for the R configurations, the sign of the associated misalignment illusion must be changed, prior to subtraction—ie the two curves of figure 4a and figure 6b are in fact added, to produce the bottom right figure shown here.

After subtraction of the pure-misalignment effect, the maxima are now more clearly located at the ±45° orientations of the arms, and the minima are near the horizontal and vertical directions of the arms (figure 6c) in the case of the L version of the standard Poggendorff configuration. In the case of the R version (figure 6d), the shape of the curve is not significantly changed, owing to the fact that the peak-to-trough variations are here substantially larger than in the pure-misalignment effect. Similar remarks apply to the obtuse-angle configurations. After correction for misalignment, the curves for the L and R configurations gain in resemblance. The data points for orientation 0.875π radians (descending obliques at −22.5° to the vertical) which were downhill in the L curves and uphill in the R curves are now uphill in both curves. A similar but less significant effect applies presumably to the 0.0π radians orientation (obliques at −45°). In other words, after subtraction of the misalignment controls, the Poggendorff illusion depends now, for its magnitude, mainly on the orientation of the arms, and not on that of the intervening configuration, in both the standard and the obtuse-angle variants. In their studies of the configurations in figures 1o and 1p, Weintraub et al (1980) also reached the conclusion that the misangulation effect there was mainly dependent upon the orientation of the arm and not on that of the intervening configuration.

3.6 *Misangulation task in the corner-Poggendorff configuration*

Figure 7 shows data for the misangulation phase of the corner-Poggendorff task. Data for configurations differing by 180° are in good agreement. The peaks are regularly positioned at the ±45° orientations of the arms, and the troughs are found at the horizontal and vertical orientations of the arms. The illusion is always positive, ie it can formally be accounted for by a law of enlargement of acute angles. Its magnitude is small, around 1.5° at peak values. In her study of the corner-Poggendorff illusion, Zambianchi (1990) found an average effect of 1.25° (she gives a value of 2.5°, which, with our conventions, corresponds to 1.25°), but found essentially no variation of the illusion with orientation.

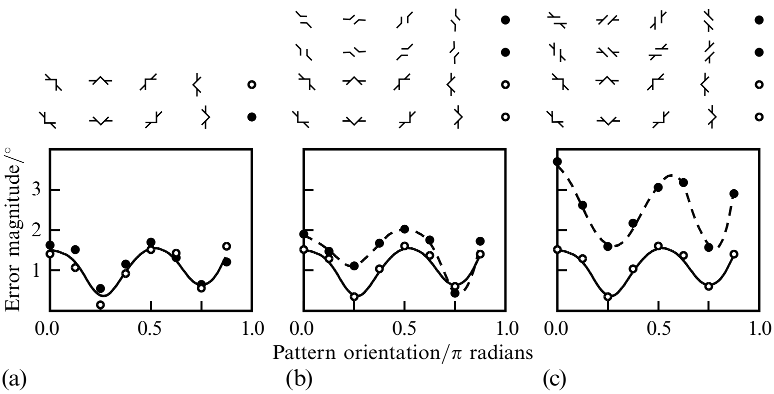

Figure 7. Misangulation in the corner-Poggendorff configuration. The results in (a) show the extent to which the arms were rotated to appear parallel. The illusion is counted positive when it agrees with a law of perceptual enlargement of acute angles. The same data are shown, after averaging, in (b) and (c) where they are compared with the obtuse-angle and standard Poggendorff misalignment data, also averaged over the configurations shown in the two rows of icons having the same symbol (black disc).

In order to compare these results with those on standard or obtuse-angle Poggendorff configurations, one needs to associate, two by two, one L and one R Poggendorff configuration, as shown in figures 7b and 7c. When the results for the L and R Poggendorff configurations are averaged, for a particular orientation of the arms, there is no need to distinguish between the primary data and the data corrected for the pure-misalignment component. This is due to the fact that a particular component counts positively when associated with the L configuration and negatively when associated with the R configuration. After averaging of the results for L and R configurations, the obtuse-angle Poggendorff data become very similar to the corner-Poggendorff misangulation data (figure 7b). The standard Poggendorff data are shifted upwards, but show the same trends (figure 7c).

3.7 *Misangulation in configurations with a single arm*

There are both L and R versions for the configurations of experiment 3 (see figures 1j – 1m), but contrary to the standard Poggendorff, these configurations are not invariant after a rotation of 180°. The illusions, measured for six subjects, are always positive; they are somewhat larger than for the standard Poggendorff, and they show greater amplitudes of variation between peaks and dips (figure 8). The collected data are in general agreement with the earlier data of Weintraub et al (1980).

The illusion is in general slightly larger with the two-line than with the one-line variant. This could be due to the incidence of a parallel-attraction effect. If one takes the average over the two sets of results, the data can be compared with the earlier data sets. Different groupings of the configurations with a single arm must be made to allow comparison with the standard-Poggendorff data on the one hand (figure 9) and the corner-Poggendorff data on the other (figure 10). There is qualitative agreement in both cases, but quantitatively the configurations with a single arm give systematically higher values. The agreement is equally good before and after subtraction of the appropriate controls (pure misalignment for Poggendorff, pointing error for the single-arm variant),

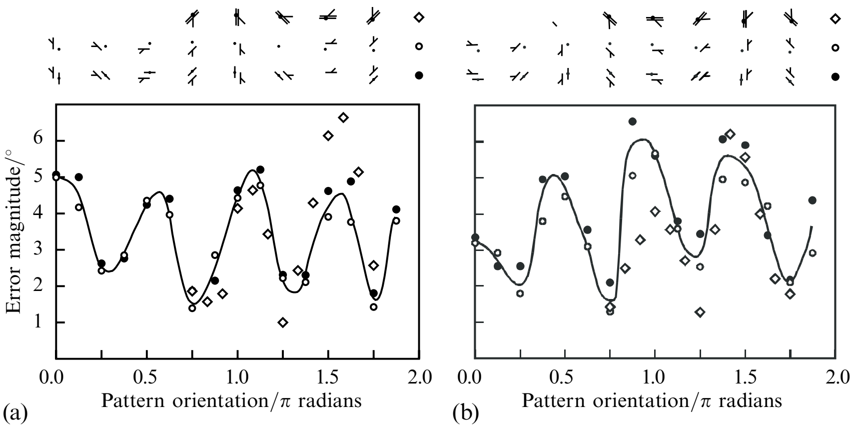

Figure 8. Misangulation in configurations with a single arm. The results for the L and R configurations are shown separately in (a) and (b). Here, black discs or unfilled circles represent averages over ten measurements by each of six subjects. The diamonds are replotted from the work of Weintraub et al (1980), and correspond to one measurement made by each of forty-eight subjects.

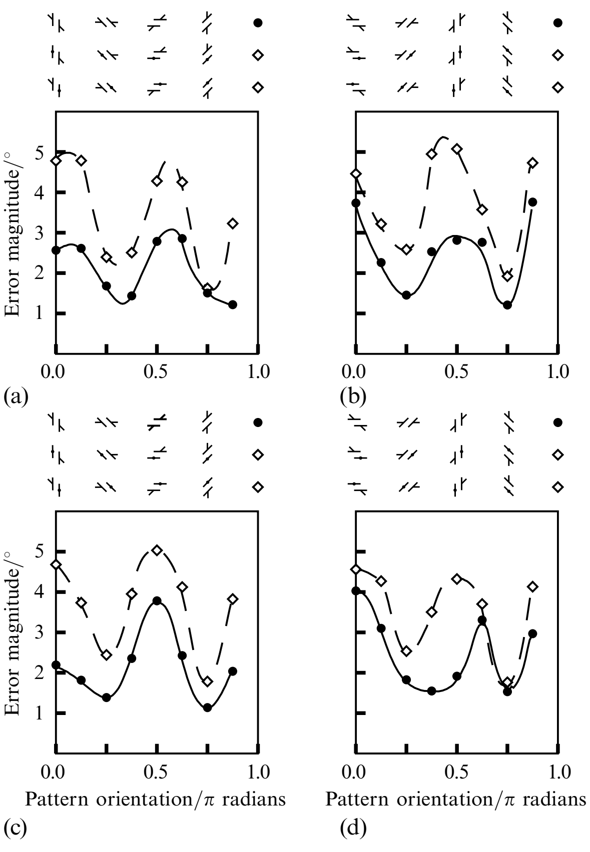

Figure 9. Comparative results. The data for the one-line (figures 1l and 1m) and two-line (figures 1j and 1k) configurations with a single arm are combined, and compared with the standard-Poggendorff data (top panels). The results for the L and R configurations are shown separately, in the left and right panels respectively. Note that a diamond in the graph represents an average taken over the two configurations shown above the graph, plus the corresponding configurations with a single line (either figure 1l or figure 1m). The same data are compared in the bottom panels, after subtraction of the misalignment component for the Poggendorff figure, and the pointing control for the configurations with a single arm.

barring the discrepancy, noted previously, relative to the R standard-Poggendorff configuration. The corrected curves for the L and R configurations with a single arm (figures 9c and 9d) again show increased similarity after the subtraction has been performed.

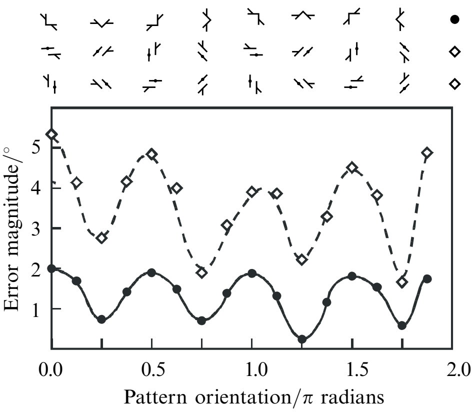

Figure 10. Comparative results. The data for the one-line (figures 1l and 1m) and two-line (figures 1j and 1k) configurations with a single arm are combined, and compared with the corner-Poggendorff data.

4 Discussion

At first, measuring the illusions at many orientations covering the plane uniformly introduces complexity in already mind-boggling data. However, the comparison of the orientation profiles brings in the end a substantial clarification of the relationship between illusions. An important factor for detecting and interpreting the relationship between profiles was the definition of the signs and magnitudes of illusions in a way which is intrinsic (axis independent) and consistent over all studied variants.

At the present stage of the analysis we are able to delineate two major components in the illusions of the Poggendorff family. A first component, which we provisionally call the 'misalignment component', is measured in configurations containing just two colinear segments (figure 1c) or a point colinear with a segment (figure 1n). A second component is a misangulation component, measured in its purest form in the corner-Poggendorff configuration (figure 1g). The positions of the peaks and the dips in the orientation profiles for the Poggendorff illusion and its variants (figures 1a, 1b, 1e, 1f, 1g, and 1j – 1m) are well explained by the two components, but their relative magnitudes require additional explanation. Pure metric effects (eg the parallel-attraction effect) constitute a third component that could help to refine the analyses, particularly in cases, not studied here, where the intervening configuration contains long parallel lines.

The pure-misalignment illusion is a small but robust effect. The data obtained by the subjects in the various controls are in good qualitative and quantitative agreement. Whether the apparent misalignment is due to shear (relative lateral shift, without orientation change) or rotation cannot be deduced from the results. We can just note that the adjustments by relative translations in the case of two colinear segments are in good agreement with the adjustments made by rotation around the endpoint of a segment proximal to the isolated point, in the case of the pointing task (figure 5b).

In the corner-Poggendorff illusion there are misangulation errors which cannot be due to lateral shifts, since, by definition, the illusion lies in the fact that the arms do not appear to be parallel. Here, the adjustment is made by effectively rotating the arms. Once this is done, there is a residual illusion, more or less compatible with a pure-misalignment illusion.

The misangulation component in the corner-Poggendorff figure is always positive (ie compatible with a trend towards orthogonality). It has a characteristic orientation profile: the maxima are located strictly at the $\pm45^\circ$ orientations of the arms, and the peaks are quite symmetric. The magnitude of the illusion at peak value is rather small (1.5°).

The results for various variants of the Poggendorff illusion (the obtuse-angle and the standard-Poggendorff configurations, and the configurations with a single arm) can be compared with the corner-Poggendorff results. To do this, results obtained independently for L and R configurations with the same orientation of the arms must be pooled together. There is therefore a loss of information, but, on the other hand, an advantage because this grouping reduces the incidence of any pure-misalignment component (such a component intervenes with one sign in an L configuration and with the opposite sign in an R configuration). When the results are regrouped in this way, the orientation profiles are all qualitatively similar, showing positive symmetrical peaks at the $\pm45^\circ$ orientations of the arms (figures 7b and 7c, and figure 10).

Let us now examine the unpooled results for L and R configurations. The primary results for the obtuse-angle and the standard-Poggendorff variants give rise to parallel plots. The illusions are positive, and the curves follow parallel courses for the two variants, the standard Poggendorff giving higher values by about 1°. The peaks and dips are shifted off the 45° obliques by 22.5°, that is, they are found at the $\pm22.5^\circ$ and $\pm67.5^\circ$ obliques, and the R curves seem inverted with respect to the L curves (figures 6a and 6b). After subtraction of the pure-misalignment component, the peaks are shifted, with one exception, back to the $\pm45^\circ$ obliques (0 and 0.5π radians in the figure). The exception concerns the R version of the standard Poggendorff for which, instead of the expected peak at the 0.5π radians value (rising $+45^\circ$ oblique), the peak seems shifted rightwards slightly in the figure (figure 6d). Barring this anomaly, for which we have no explanation, the four curves for L and R versions of the standard and obtuse-angle Poggendorff now follow similar courses (figures 6c and 6d).

The primary results for the L and R versions of the single-arm variants are perhaps more complex, presumably because there are more orientations to take into account. The two-line (figures 1j and 1k) and one-line (figures 1l and 1m) variants follow parallel courses, and the results are in good agreement with those obtained earlier by Weintraub et al (1980). The illusion is slightly larger with the two-line variants, which might be due to the parallel-attraction effect. [Note that for this subset of six subjects the difference between standard and obtuse-angle Poggendorff results are also rather small (data not shown).] The results for the L or R configurations can be associated by pairs, in order to be compared with those for the standard L and R Poggendorff configurations. There is good agreement between the two sets of data (figures 9a and 9b). After subtraction of the misalignment control for Poggendorff and pointing control for the configurations with a single arm, all four curves agree, except for the above-mentioned anomaly, concerning the shifted peak of the R standard Poggendorff. Otherwise, the data for the configurations with a single arm look even more regular and symmetrical than the standard-Poggendorff data.

The notion that the Poggendorff figure involves several contributing elementary illusions is not new. Hotopf and Hibberd (1989) studied several variants of the Poggendorff figure and determined how the strength of the illusion varied with the length of the arms. They distinguished five components: (i) a 'horizontal – vertical assimilation tendency', (ii) a 'horizontal-bias alignment effect', (iii) 'attraction-caused alignment illusions', (iv) 'angle-caused alignment illusions', and (v) a 'very-short-induction-line (VSIL) misalignment illusion'. (i) and (ii) taken together correspond to our 'pure-misalignment component', (iii) corresponds to our 'make-square' controls, (iv) corresponds to our 'misangulation component', and (v) is not relevant in our study, where the arms used were not short enough to produce such an effect. Concerning pure-misalignment figures, Hotopf and Hibberd noted that, according to the way the two segments are completed to form a Poggendorff figure, the component acts either in the direction of the standard-Poggendorff illusion or against it. We exploited this feature to pool the data so that positive and negative contributions would cancel out. The study of Hotopf and Hibberd also speaks in favour of misangulation as a major determinant of the illusion. We showed in fact that most of what we measure in standard-Poggendorff configurations must be due to misangulation.

Let us now try to explain the hierarchy in the strengths of the illusions. We believe that an illusion can be strong in one configuration and weak in another when the second configuration provides clues against the illusion. Thus, although misangulation is measured in its purest form in the corner-Poggendorff configuration, it is rather weak there because it violates the parallelism of the two arms. Parallelism is possibly one of the strongest primitives in vision (see eg Ninio 1977; Stevens 1986) and it is conceivable that in case of conflict, parallelism judgments take the precedence over orientation judgments. One argument raised in the past against a misangulation effect in the Poggendorff illusion was that a third segment, outside the configuration and parallel to the colinear segments, still looked parallel to them (Hotopf and Ollerearnshaw 1972). One could argue that parallelism is not perceptually violated in these experiments because misangulation could be a very local effect at the intersection between the arm and the body, but then, why would it be violated in the corner-Poggendorff variants? If, as we believe, parallelism judgments tend to override misangulation effects, we can maintain the idea that misangulation is fully present in the Poggendorff illusion (in which it is not directly measured), and reduced in the corner-Poggendorff configuration, in which it is measured independently of other effects.

Next, why are the illusions stronger in the configurations with a single arm? If the two misangulations on the two sides of a Poggendorff configuration are unequal, this will generate a deviation from parallelism which again will be a counteracting clue. However, this explanation can account for only part of the difference. Another possibility to consider is related to the fact that, in our tests for the standard and obtuse-angle Poggendorff configurations, the adjustment is made by a relative sliding of the two half configurations. If there are 'colinearity detectors' in the brain, as implied by recent psychophysical work (Field et al 1993; Polat and Sagi 1994; Wehrhahn and Dresp 1998) then adjustment by sliding is likely to give systematically lower estimates than adjustments by rotation.

What remains to be explained is the difference between standard and obtuse-angle Poggendorff results. One of the major current theories concerning the Poggendorff illusion is that it is due to low-pass filtering at the junction between the arm and the body, a phenomenon which would mainly influence estimations for acute but not obtuse angles (eg Morgan and Casco 1990). This theory may account for the difference (thus adding one more component to the illusion) but not for the existence of an illusion in the obtuse-angle configuration, which seems to follow the same general trend as the illusion in more strongly acting configurations.

A fortunate circumstance in this work was that different effects led to different orientation profiles. When averaged over the subjects, some tests yield both positive and negative values, some profiles have peaks and dips at all $\pm 22.5^\circ$ and $\pm 67.5^\circ$ orientations of the obliques, others have their peaks at the $\pm 45^\circ$ orientations and their dips at the horizontal and vertical orientations. Furthermore, metric effects such as the horizontal – vertical anisotropy are clearly distinguishable from orientation effects. The individual subjects' curves show even greater variability, and our initial hope was to carry out our analyses for each individual subject. However, it turned out that to account for the individual subjects' responses, it was necessary to suppose that the relative weights of the different components of the illusion could themselves be subject and orientation dependent. Presumably, it will be necessary to test a still greater range of illusions to be able to construct a predictive model of an individual subject's responses.

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