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Going round in circles: shape effects in the Ebbinghaus illusion

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Abstract—The Ebbinghaus illusion has traditionally been considered as either a sensory or a cognitive illusion, or some combination of these two. Cognitive contrast explanations take support from the way the illusion varies with the degree of shape similarity between the test and inducing elements; we show, however, that contour interaction explanations may account for this result too. We therefore tested these alternative theories by measuring the illusion with different test shapes as well as different inducer shapes, in all combinations. We found that for angular or hexagonal test shapes there is no similarity effect, and for some shape combinations there is no significant illusion, in contradiction to both of the traditional hypotheses. Instead, we suggest that an integrated model of visual processing is needed to account for the illusion.

Keywords: Ebbinghaus illusion; visual illusions; cognitive contrast.

1. INTRODUCTION

The Ebbinghaus illusion (also known as the Titchener circles) consists of a change in the perceived size of a circle in the presence of nearby nonconcentric circles of larger or smaller area. Demonstration of the effect is usually given by surrounding one of two identical circles with large elements and the other with small elements, and by showing that the first now appears smaller than the second. This phenomenon illustrates a very general finding: perception of an object is at least partially based on its relations with the stimuli that form its context. Unfortunately, however, no single hypothesis has been shown sufficient to explain the Ebbinghaus phenomenon.

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1.1. Cognitive size contrast

Massaro and Anderson (1971) accounted for the Ebbinghaus anomaly in terms of a cognitive mechanism of size contrast, which alters the apparent size of the test circle, exaggerating its relative smallness or largeness relative to the figures surrounding it.

Support for such a judgmental mechanism comes from an ingenious experiment by Coren and Miller (1974). These authors surrounded a test circle with a ring of four larger or smaller identical figures that differed in degree of similarity to the centre circle. (The degree of similarity was measured by asking subjects to rate it.) The surrounding figures were circles, hexagons, triangles, or angular shapes, which were chosen to form a sequence along an ordinal scale of shape similarity. The Ebbinghaus effect was found to vary as an increasing function of the similarity between test and inducing elements. On the assumption that it is more likely for the visual system to make comparisons among similar targets than dissimilar ones, Coren and Miller considered their results as supportive of a judgmental process of comparison (see also Coren and Enns, 1993).

Choplin and Medin (1999) have recently qualified this conclusion, claiming that Coren and Miller's notion of 'similarity' was insufficiently well characterized. Choplin and Medin instead found that only the similarity of the figure perimeters affected the magnitude of the illusion; the degree of similarity in internal structure between the test and inducing figures was of no consequence. They suggested that the perimeters or silhouettes of objects are crucial because they contain sufficient information to categorize the objects. This permits an efficient estimation of the relative sizes of several objects from the same category, without having to commit computational resources and time for a full semantic categorization of the whole object.

Certain problems remain however with cognitive judgement theories, such as why the illusion strength varies with the brightness of the lines (Cooper and Weintraub, 1970; Jaeger and Pollack, 1977; Jaeger and Grasso, 1993), with the number of inducing elements and with their separation from the central test figure (Massaro and Anderson, 1971; Girgus *et al.*, 1972; Jaeger, 1978; Weintraub, 1979; Jaeger and Grasso, 1993). Additional hypotheses have to be invoked, such as (*ad hoc*) changes in the weighted averaging of the element sizes (Massaro and Anderson, 1971; Pressey and Murray, 1976) or processing only within a focal aperture of (*ad hoc*) variable size (reviewed by Shulman, 1992).

1.2. Contour interaction

The alternative tradition posits that the Ebbinghaus effect is due to a more fundamental, sensory process which causes perceived displacement of visual contours via a mechanism operating on a spatiotopic encoding of the stimulus, as opposed to an object file or a semantic level of encoding. According to this tradition, if contour attraction is an increasing function of proximity and length of inducing contour, the Ebbinghaus test figures should apparently increase in size when surrounded by small, as opposed to large, circles. This principle on its own, however, is obviously not adequate. Firstly, it predicts expansion of the test figure and not contraction, yet contraction has frequently been demonstrated (a finding we replicate here). Secondly, with inducing circles of the same size as the test circle, there should be expansion of perceived test size; but this is not observed (e.g. Massaro and Anderson, 1971; Girgus *et al.*, 1972; Weintraub, 1979; Jaeger and Grasso, 1993).

To permit the integration of such apparently contradictory data, two solutions have been proposed. The first is a mixed model. According to this idea, all contours attract (making the test circle seem larger), but at the same time object context leads to size contrast. When the surrounding circles are large, the contextual contrast overrides contour attraction and makes the test circle seem smaller (e.g. Girgus *et al.*, 1972; Jaeger and Pollack, 1977; Weintraub, 1979; Jaeger and Grasso, 1993).

The second model is a biphasic interaction model. When evaluating the strength of the two main theories empirically, Jaeger (1978) found no evidence for Massaro and Anderson's (1971) cognitive size contrast explanation. His data showed, contrary to the hypothesis, that (i) the illusion is insignificant if the test and inducer circles are presented successively (with 500 ms inter-stimulus interval), (ii) with large inducers their number has no effect on the strength of the illusion, and (iii) with a few (2 or 4) small inducers the test circle appears reduced in size. Instead, Jaeger concluded that the inner and outer portions of the large surrounding circles have antagonistic effects on the apparent size of the test circle, generating respectively overestimation and underestimation. This idea is in accord with biphasic models of the interactions between contours, like those of Eriksson (1970) and Brigner (1977), and is supported by later psychophysical studies which have indeed demonstrated directly that nearby contours attract, those at intermediate distances repel, while very distant ones show no interaction (e.g. Badcock and Westheimer 1985a, b; Hock and Eastman, 1995; Bondarko and Danilova, 1999).

However, the biphasic contour interaction hypothesis cannot explain the similarity effect discovered by Coren and Miller (1974). In their experiments there were different amounts of contour at different distances from the test circle, depending on the inducer shape. For example, the circular inducers had less far-away contour than the angular inducers (Fig. 1), so should have reduced the perceived size of the test circle less; yet the opposite result was obtained. The magnitude of this effect may however be small, because there is also more inducing contour near the test figure. (This is because, for a constant area, any angular figure has a longer perimeter contour than a circle, and this extra contour exists both near to and far from the test circle.) So, according to the hypothesis, this extra contour enhances the attraction caused by the inner segment of the inducing figure. However, this is counterbalanced by the enhanced repulsion caused by the increased length of the outer segment. The overall result thus depends on the quantitative parameters of how attraction and repulsion fall off as a function of distance between

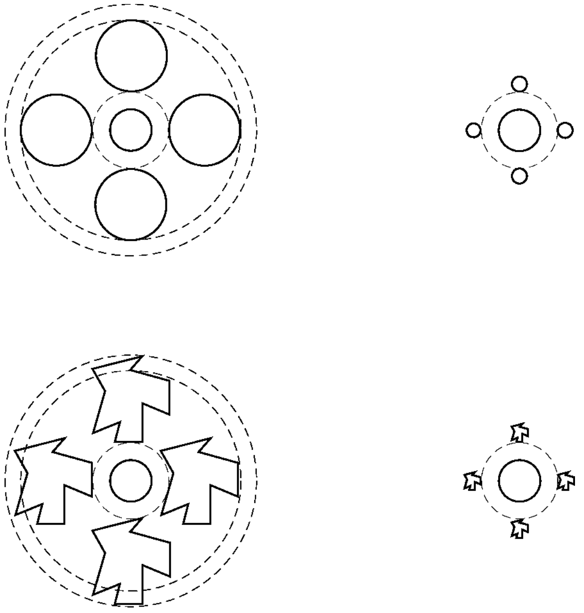

Figure 1. Solid lines show Coren and Miller's (1974) figures with circles (upper part) *versus* angular shapes (lower part) as inducers. The inner dashed circles are the same diameter in every case and demonstrate the constant distance between the test circles and the proximal point of each inducer. The larger pairs of dashed circles are the same in the upper and lower parts of the figure. They pass through the most distal points of the inducers (the outer dashed circle for the lower part, the next dashed circle for the upper). The gap between these two dashed circles demonstrates that the inducing angular shapes contain more distal contour than the inducing circles.

contours; but these parameters have never been quantified for the Ebbinghaus illusion. On balance, the effects of inducer shape in Coren and Miller's stimuli should be slight, since deviations from a circular shape, keeping constant area, introduce additional amounts of both closer-in and further-away contour. However, empirically the effects of shape are large, which argues against contour interaction explanations.

In addition, consider again the case with equal-sized test and inducing circles. To account for the result that there is no change in perceived size of the test circle, the balance between attraction and repulsion must be fairly exact. However, as the distance between test and inducers increases, there is only a slight drop in the perceived size of the test circle, and this is true over a range several times the diameter of the inducing circles (with large or small inducers; Massaro and Anderson, 1971; Girgus *et al.*, 1972; Weintraub, 1979; Jaeger and Grasso, 1993). Also, there is no obvious change in the illusion with viewing distance (Jaeger, 1999). Therefore the boundary between the zones of attraction and repulsion is not fixed in degrees of visual angle, but must move to take account of test-inducer separation so as to maintain the balance between attraction and repulsion. Thus the boundary

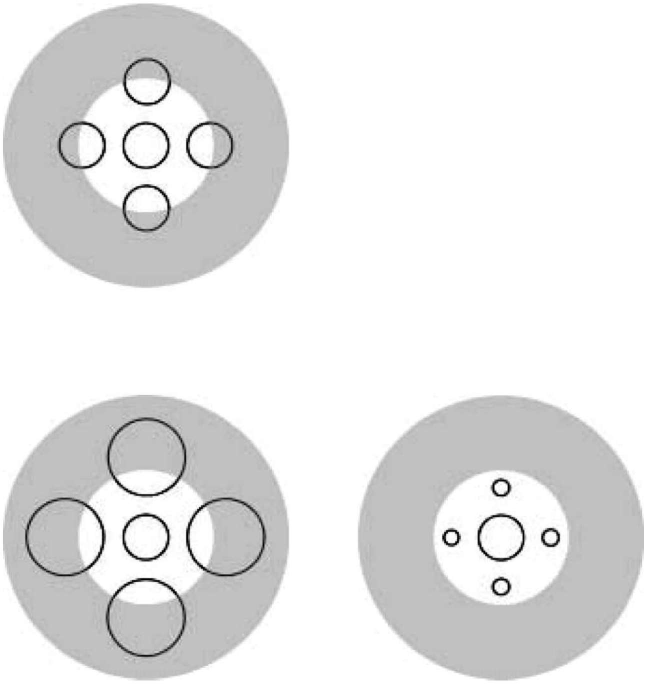

Figure 2. Shaded annuli show putative regions of repulsion, surrounding an inner area of attraction. At the top, inducer circles (equal in size to the test circle) fall across both zones, and thus induce equal amounts of repulsion and attraction, giving no overall effect on the test circle's perceived size. Below, the same size grey zone is shown with larger (on the left) and smaller (right) inducing circles to show how this theory accounts for the Ebbinghaus illusion. With large inducer circles, there is more contour in the repulsion zone, so the test circle is seen as smaller; and the opposite is true with the small inducers.

is adjusted so it (approximately) bisects the inducer circles. However, why then does an illusion arise when the inducers are of different size (Fig. 2)? Why is the boundary between the attraction and repulsion zones not adjusted to bisect the inducer circles again?

One mechanism which has been suggested to account for these effects in the Ebbinghaus and other assimilation/contrast illusions is a variable-diameter focus of 'attention', with assimilation within a central zone and repulsion/contrast in a surrounding annulus (Pressey and Murray, 1976; Coren and Porac, 1983; Jordan and English, 1989; Pressey and Pressey, 1992; Shulman, 1992; Jaeger, 1999). The size of the focus is however calculated on an *ad hoc* basis to fit the data. Another idea is that judgements of the size of the focal item (i.e. the test circle in the Ebbinghaus) are made relative to the overall diameter of the whole array of shapes (the 'frame'; Pressey and Murray, 1976; Brigell and Uhlarik, 1979; Weintraub and Schneck, 1986; Pressey and Pressey, 1992; Ehrenstein and Hamada, 1995). These framing ratio hypotheses could predict the results of Coren and Miller's

(1974) study, at least qualitatively, since the inducing circles, hexagons, triangles and angular shapes, in that order, subtended progressively larger overall dimension. However, the various framing ratio hypotheses disagree whether it is the horizontal, the vertical, or the longest dimension that sets the frame's 'size', and there are 'peculiar' interactions, asymmetries and oblique effects (Ehrenstein and Hamada, 1995) which make the theory problematic. Both these answers, the attentional and the framing ratio hypotheses, are however holistic and cognitive rather than local and sensory in nature, and are thus both liable to the criticisms raised at the end of Section 1.1. We have thus come full circle back to the type of judgemental theory from which we started, and which we and others have rejected.

1.3. The present experiment

In the present experiment, Ebbinghaus figures are constructed in which the inducers are circles, hexagons, triangles or angular shapes and the test figure is also a circle, a hexagon, a triangle or an angular shape. In this situation, which has not been tested before, one prediction of the cognitive similarity account is that the size of a test angular shape will be mis-estimated maximally when the inducing figures are angular shapes and very little when the inducing figures are circles. On the other hand, the spatiotopic contour interaction theory predicts that different inducing shapes should be about equally effective in 'attracting' or 'repelling' test contours regardless of how similar they are to the central figure.

2. METHODS

2.1. Apparatus and stimuli

The four outline elements selected by Coren and Miller (1974) were used to construct thirty-two different figures (four test shapes by four inducer shapes by two inducer sizes, either larger or smaller than the test shapes). Each stimulus configuration consisted of a central test figure (a circle, a hexagon, a triangle or an angular shape) surrounded by four inducing figures (four circles, four hexagons, four triangles or four angular shapes). The central test figure had an area of 154 mm^2 (corresponding to a diameter of 14 mm in the case of the circle). The large inducing figures each had an area of 450 mm^2 and the small inducing figures each had an area of 20 mm^2. The distance between proximal edges of central and context figures was always 6 mm. (Sizes and distances were intentionally chosen to be equal to those used in Coren and Miller's study.)

Stimuli were generated by a Tektronix 4054 Graphic Computing System and presented on a 19-inch high resolution display. All figures were drawn with bright green lines about 0.5 mm wide and appeared on a dark background. The eye-to-display distance was about 60 cm.

2.2. Procedure

On each trial, one of the 32 possible stimulus configurations and a comparison figure were presented. The comparison figure, which was identical in shape to the test figure, could be adjusted to match the apparent size of the test figure. The observer varied the size of the comparison figure by pushing one button to increase it and one to decrease it. The initial size for each adjustment was randomly chosen to be either well above or below the right size; each pressing of a button changed the figure size by 1 percent.

Five volunteers with normal visual acuity served as subjects. They were allowed free eye movements and could look back and forth between the stimulus and the comparison figure. In a single experimental session each of the 32 stimulus configurations was presented once, in random order; five separate sessions were run on each subject.

3. RESULTS

The raw data expressed percentage deviations from the point of objective equality, which was conventionally set to zero. So mean values higher and smaller than zero indicate respectively an effect of over- and under-estimation. Following Coren and Miller (1974), we calculated the ‘overall’ illusion magnitude by adding the effects of large and small inducers to simulate the normal viewing condition where two identical test shapes are compared simultaneously, with each surrounded by different size inducers. The results are presented in Table 1 for every possible combination of test and inducing shapes.

First, we compared the magnitude of the classical Ebbinghaus illusion (which is traditionally displayed with circles) with the illusion engendered by other shapes (i.e. with identical shapes for both test and inducing elements). Interestingly, we found that the effect depends on the shape of the elements: it is considerably larger with triangles (mean = 6.08) or circles (mean = 5.60) than with hexagons (mean =

Table 1.
Mean magnitude (percent) of the Ebbinghaus illusion for all possible combinations of test (across) and inducing (down) element shapes

		Test shape							
		Circle		Hexagon		Triangle		Angular	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE
Inducer shape	Circles	5.60	0.91	3.44	0.70	1.36	0.64	0.56	0.89
	Hexagons	4.16	1.09	2.76	0.80	3.48	0.48	2.36	0.70
	Triangles	3.04	0.65	1.72	0.52	6.08	0.83	0.00	0.74
	Angular	2.56	0.53	1.76	0.99	2.52	0.65	1.60	0.44

2.76) or angular shapes (mean = 1.60); $F(3, 12) = 11.70$, $p < 0.001$. Figure 3 illustrates the displays with all-isomorphic shapes.

Then we compared the illusion magnitudes observed in the same-shape Ebbinghaus figures with those observed in the different-shape ones, to test whether shape isomorphism *per se* has any effect. Test circles were subject to larger illusions when surrounded by circles (mean = 5.60) than when surrounded by any other shape (mean = 3.25, averaged across hexagons, triangles and angular shapes), $t(4) = 2.99$, $p = 0.04$. The same held true for test triangles (means were 6.08 *vs* 2.45, $t(4) = 3.00$, $p = 0.04$). However, there was no significant similarity effect with either hexagons (2.76 *vs* 2.31, $t < 1.3$) or angular shapes (1.60 *vs* 0.97, $t < 1.0$) as test figures.

Coren and Miller's original finding was replicated: when the test figure was a circle, the Ebbinghaus effect was largest if the inducing figures were also circles (mean = 5.60), and gradually decreased for inducing hexagons (4.16), triangles (3.04), and angular shapes (2.56); linear trend $F(1, 4) = 11.42$, $p = 0.03$. When the test figure was an angular shape, however, the similarity hypothesis predicts that the effect be maximal for inducing angular shapes and monotonically decrease for triangles, hexagons, and circles; but the corresponding illusion magnitudes were respectively 1.60, 0.00, 2.36, and 0.56; linear trend $F(1, 4) = 0.03$, $p = 0.89$. With test hexagons or triangles the trends should not be linear, because the circular and angular shapes differ from them in opposite directions; however, quadratic trends should be apparent. For triangles, the similarity hypothesis is supported: linear $F(1, 4) = 2.58$, $p = 0.18$; quadratic $F(1, 4) = 34.37$, $p = 0.004$; but for hexagons the hypothesis is rejected: linear $F(1, 4) = 9.43$, $p = 0.037$; quadratic $F(1, 4) = 0.58$, $p = 0.49$.

4. DISCUSSION

The pattern of results shows several interesting features, of which the most salient is the fact that the Ebbinghaus illusion is highly dependent on the shapes of both the inducing and the test elements. Our results cannot be described by any single general principle, but they do have implications for the current theories of the Ebbinghaus illusion.

4.1. The cognitive contrast hypothesis

Our data are inconsistent with the predictions of the cognitive contrast hypothesis. Firstly, same-shape illusions (i.e. with identically shaped test and inducing elements) were not equally strong for all shapes. Secondly, same-shape illusions were significantly larger than different-shape illusions only for circles and triangles as test stimuli. Thirdly, there was no degree-of-similarity effect with angular or hexagonal test stimuli, in that progressive decreases in similarity did not lead to systematic decreases in illusion magnitude. The fact that the similarity effect cannot be generalized across shapes speaks against the figural/shape (Coren and Miller, 1974),

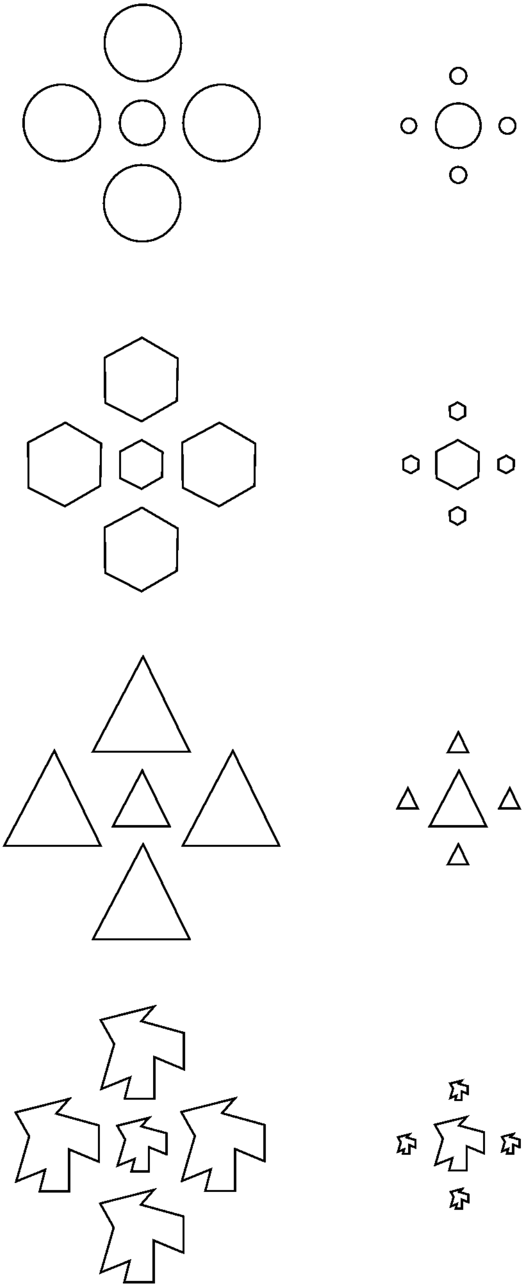

Figure 3. The Ebbinghaus illusion with test and inducing shapes identical, for each of the four shapes used by Coren and Miller (1974). The shapes were traced from Fig. 1 of that paper and scaled to have equal areas for all the test elements (and similarly for the large and for the small inducing elements).

conceptual/semantic (Coren and Enns, 1993) and perimeter (Choplin and Medin, 1999) similarity hypotheses. Finally, the fact that inducer shape had any effect at all argues against even a general size contrast explanation that would apply to any pairs of stimuli regardless of their degree of similarity. This last point is also supported by our analysis of the separate effects of large and small inducers (with identical test and inducing shapes): perceived size distortions were significant with circular and with hexagonal shapes only when the inducers were large, with triangular shapes only when the inducers were small, and with angular shapes under neither size of inducer.

Our results also speak against cognitive accounts of the variability of the illusion with attention or with the overall size of the 'frame'. These theories were developed to deal with the relatively small changes that occur in the illusion with large changes in test-inducer separation. In our experiments, in contrast, we found relatively large changes in the illusion (Table 1) with small changes in the overall dimensions of the frame (due to changes in shape: Fig. 1).

4.2. The contour interaction hypothesis

The spatiotopic contour interaction hypothesis, even in its more complex, biphasic variant, is inadequate to explain the Ebbinghaus illusion. Our data show that attraction/repulsion cannot be a unique function of the amount of contour present at a given distance. For a ring of contextual inducing figures of any given shape, the absolute and relative quantities of far-away and close-in contour do not change much across central figure shape; yet size mis-estimation of the test figure varies enormously (look along each row in Table 1).

Even if amounts of contour do not change, many other things in these displays do, which confuses interpretation in terms of the hypothesis. Two potential sources of variance should be mentioned which are inevitable when one uses these kinds of figures.

(a) The actual distances between test and inducing contours vary within and between shapes. Coren and Miller (1974) decided to keep constant the shortest distance between proximal edges of test and contextual figures. This choice is probably as good as any other; still, it is obvious that neither the longest distance nor the average distance between these edges is constant across stimulus configurations. This is also true within single-shape configurations, with the only exception of the circle-circle displays in which test and contextual shapes are vertically and horizontally symmetrical.

(b) The orientations of contours with respect to each other vary within and between shapes. Pollack (1964) found that the attraction between non-intersecting contours was maximal when they were parallel, and gradually decreased as the angle of projected intersection of boundaries increased. Attraction changed to repulsion for angles larger than 30 deg and was maximal when the contours formed an angle of 90 deg. Yet, a hypothesis of this sort predicts that the test figures ought to shrink when surrounded by certain shapes and enlarge when surrounded by others, regardless of the sizes of such inducers, because the relative orientations of the boundaries would be the same for large and small inducers. This clearly is not the case. Additionally, the concentric-circles Delboeuf illusion, in which 'adjacent' contours can be said to run in parallel, shows many characteristics in common with the Ebbinghaus (Morinaga and Noguchi, 1966; Girgus *et al.*, 1972; Girgus and Coren, 1982; Weintraub and Schneck, 1986).

5. CONCLUSIONS

We began by considering cognitive contrast explanations of the Ebbinghaus illusion. In particular, we examined support for this explanation based on the degree of similarity between the test and inducing figures (Coren and Miller, 1974). Then we considered contour interaction explanations for the Ebbinghaus illusion, including additive and biphasic models.

None of these is consistent with the data obtained in our experiment. The contour interaction hypotheses are not well characterized, yet they cannot explain our data, even when several alternative interpretations are considered. The same is true for the cognitive contrast idea, which fails to account for the inconsistent effects of similarity, however similarity is interpreted.

What then is the source of the Ebbinghaus illusion? Some workers have concluded that multiple mechanisms must be at work, since none alone is able to account for all the phenomena (e.g. Weintraub and Schneck, 1986; Ehrenstein and Hamada, 1995). However, rather than pursuing additive models such as these, where several components are proposed which contribute variable (and arbitrarily weighted) amounts to the illusion under varying circumstances, we suggest that the illusion should be approached in the light of recent developments in our understanding of the visual system. These show that the division between 'sensory' and 'cognitive' mechanisms is not so clear cut. Instead, there is dynamic interaction between processes at all stages of analysis of the retinal image, and even very early stages are subject to 'top-down' influences (e.g. Ahissar and Hochstein, 2000; Deco and Schürmann, 2000; Rose and Pardhan, 2000; Suder and Wörgötter, 2000). These may account for the observation that the Ebbinghaus illusion is subject to factors such as attention (Shulman, 1992) and practice (Girgus and Coren, 1982). With such complex dynamic processes at work, the behaviour of the visual system is highly non-linear and thus difficult to predict without quantitative modelling and simulation.

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