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Contrast polarities determine the direction of Café Wall tilts

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Abstract. We propose an explanatory approach to Café Wall type illusions that is simple yet fairly comprehensive. These illusions are constructed out of basic elementary units in a jigsaw-like manner. Each unit, in general, contains both a solid body and a thin tail: the contrast polarity between the two determines the direction of the contributory illusory tilt produced by that element—according to a heuristic rule illustrated in figure 1. Ensembles of these elements exhibit illusory tilts only when the tails of the elements align along a common line in an additive manner. When elements of opposing polarity alternate, the illusion is cancelled. This approach extends and supersedes those presented in Pinna's illusion of angularity and Kitaoka's 'acute' corner effect. Furthermore, it appears to be, in part, compatible with existing mechanisms proposed to account for the emergence of local tilt cues, and it suggests several novel variations on the Café Wall theme.

1 Introduction

We propose an explanation for Café Wall type illusions that is simple yet fairly comprehensive. Our method is one of graphical construction, so the level of explanation remains purely phenomenological. Nevertheless, the very simplicity of our approach ought to inform and complement other lines of approach, be they physiological or computational.

We begin by observing that most Café Wall type stimuli can be composed, like jigsaws, out of unitary elements, each of which topologically conforms, more or less, to the spatial structure shown in figure 1A. At its most basic, that structure should exhibit a solid area of uniform colour (here the black brick) and a nearby thin line (here the short black bar). Composition occurs by placing units so that the bars align along straight lines. These lines need not be fully connected—as will be demonstrated—but must be well enough aligned so that the normal perceptual grouping processes consider them as parts of the same single straight line. Café Wall stimuli usually contain two or more such lines, placed parallel to each other, and the illusion arises if they are seen other than parallel. The lines are typically seen straight but tilted from their true physical orientation. This tilt distortion might be attributed to the proximity of the blobs to the lines, since, if the blobs are moved away, the lines lose any tilt.

It may, indeed, be useful to consider the solid area furnished by each unitary element as a potential locus of distortion. Any straight line trajectory (real or 'subjective') that passes in close proximity to that locus then receives a small contribution to its tilt. For example, the unit shown in figure 1A would produce a slight counterclockwise tilt. Yet this tilt clearly does not manifest itself locally. On the contrary, any distortion seems to act upon the trajectory in a global manner; the loci occurring

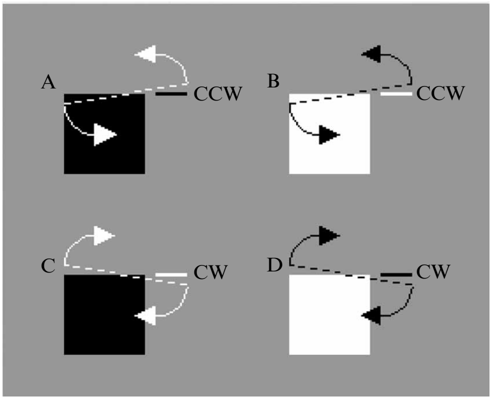

Figure 1. Our rules for the combinations of contrast polarities of edges and of lines for the Café Wall tilt. The upper line of each unit appears to tilt in the direction indicated by arrows and broken lines. CW means a clockwise tilt while CCW indicates a counterclockwise tilt.

along a line's length can be thought to integrate their individual contributions so that they express a single, uniform, highly visible tilt—as would be achieved by the 'collector units' proposed by Morgan and Moulden (1986). Figure 8A shows that this may occur for local tilts not seen as illusory.

Whether a unit produces a counterclockwise (CCW) or a clockwise (CW) tilt appears to depend not only on its spatial orientation (eg a mirror image of figure 1A yields a CW tilt) but also on the contrast relation between the solid area and its adjacent line. In particular, the tilt seems to flip from CCW to CW if the area and the line are of opposite contrast polarities (figures 1C and 1D), but not if they both simultaneously changed from negative to positive contrast (figure 1B).

Accordingly, it ought to be possible to cancel any tilt effect by simply alternating CCW and CW contributory units along the edge of any line trajectory. Figures 5C and 5D demonstrate this with minimum stimuli, each containing a single trajectory (created by abutting two rows of units). Note that other varieties of Café Wall illusion may be demonstrated and understood in the same fashion.

These phenomenological explanations were partly presented in Pinna (1990a) and Kitaoka (2001).

2 History of Café Wall type illusions

The Café Wall illusion (figure 2A) was first demonstrated by Fraser (1908) and named so by Gregory and Heard (1979). This illusion has been extensively studied from a variety of viewpoints. Helmholtz irradiation (apparent greater size of a white area than of a black one) was often used as an explanation (Münsterberg 1897; Pierce 1898; Moulden and Renshaw 1979). Gregory and Heard (1979) proposed a border-locking

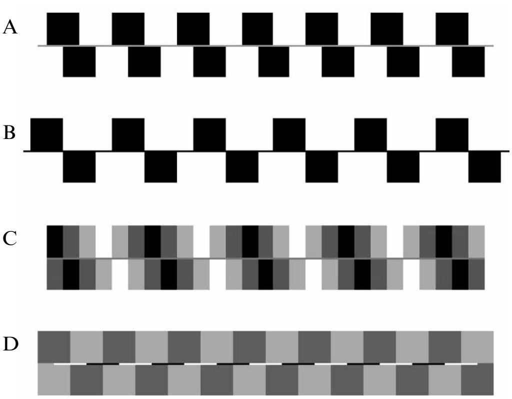

Figure 2. Ensemble of elements: A, the Café Wall illusion; B, the checkered illusion; C, the illusion of shifted gradations; D, the illusion of striped cords. The middle horizontal line of each figure appears to tilt CCW.

theory whereby the pull of white into neighbouring black areas (via irradiation) would be mediated across a neutral centre line only in certain places, thus generating the required pivotal local tilt. That approach was recently reconsidered and criticised by Roncato (2000). McCourt (1983) pointed out the role of brightness induction (grating induction) on the formation of 'twisted cords' in the straight trajectory line. Morgan and Moulden (1986) generated 'twisted cords' by applying bandpass filtering. That line of study was refined by Lulich and Stevens (1989) and Earle and Maskell (1993). Stuart and Bossomaier (1992) discussed cooperative coding involved in global formation of the tilted trajectory lines. Takeuchi (1997) showed a motion analogue of the Café Wall illusion, which may be related to the Ouchi illusion (Spillmann et al 1986; Hine et al 1995; Khang and Essock 1997). Most recently, Prinzmetal et al (2001) attempted to attribute the Café Wall illusion to the Zöllner illusion, though this idea had been previously depreciated by Stuart and Bossomaier (1992).

Leading up to the present study, Pinna (1990b, 1991) presented the illusion of angularity (figure 3), which can be understood by using the same elemental composition approach. Moreover, Kitaoka (1998) implicated the 'acute' corner effect (figure 4), where illusory tilts were attributed to the apparent contraction of edge corners (Pierce 1898; Moulden and Renshaw 1979). Although that idea has now been superseded by the approach presented here, it did usefully suggest three novel variations, that anticipate further discussion in sections below: the checkered illusion (figure 2B), the illusion of shifted gradations (figure 2C), and the illusion of striped cords (figure 2D).

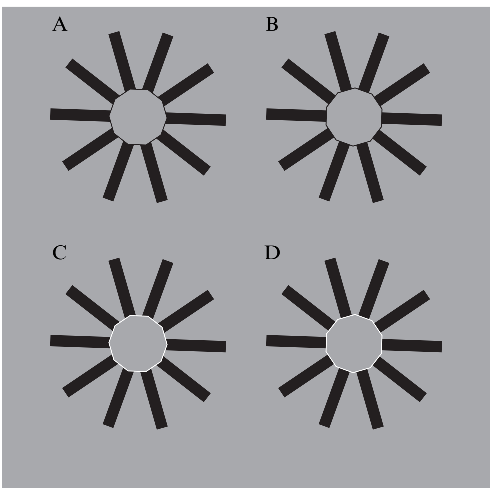

Figure 3. The illusion of angularity: A, when the apices of a polygon of black lines are placed on the black bars, the polygon looks more acute; B, when the apices are placed on the background, the polygon appears less acute; C and D, when the contrast polarity of the polygon is reversed, the illusion of angularity is also reversed.

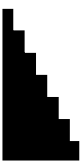

Figure 4. An example of the corner effect. Each corner of the 'staircase' is the right angle but appears to be slightly acute.

3 Explanation of Café Wall type illusions

Figure 5A confirms that a trajectory line need not be fully continuous for the effect to arise. It exhibits a CCW illusory tilt of roughly the same magnitude as that shown in the original Café Wall illusion (figure 2A), despite the fact that the trajectory line is considerably fragmented. Indeed the bars of our elementary unit can even be substituted by rounded dots (figure 5B—Kitaoka et al 2001) as long as a straight trajectory passes through their central loci.

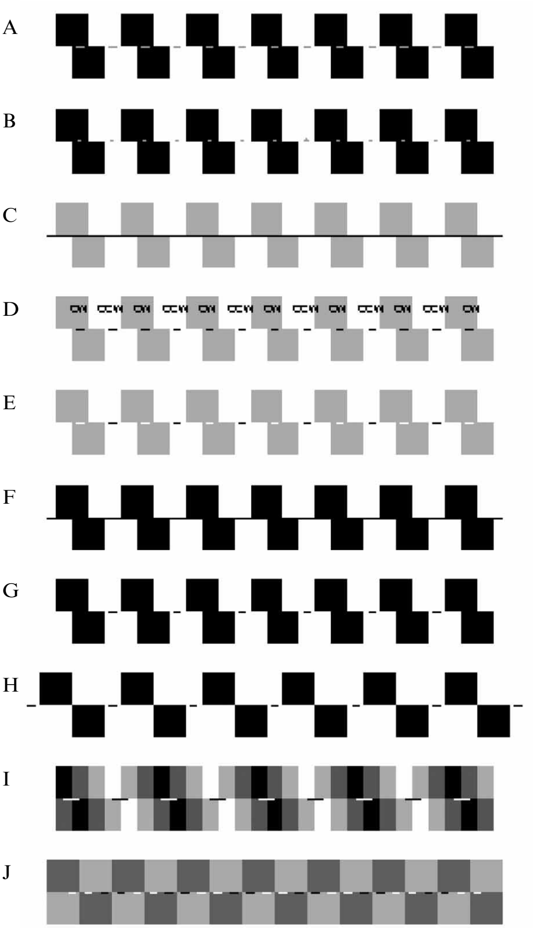

Figure 5. A, fragmented version of the Café Wall illusion, in which the horizontal row of line segments appears to tilt CCW; B, demonstration that even dots are sufficient to generate illusion; C, an example which does not produce illusion; D, analysis of local tilts of C—alternating clockwise (CW) and counterclockwise (CCW) cancels any tilt; E, alternating tail contrast restores the illusion; F, the Münsterberg illusion, in which the horizontal black line appears to tilt CCW; G, its fragmented version; H–J, fragmented versions of the checkered illusion, of the illusion of shifted gradations, and of the illusion of striped cords. Middle lines appear to tilt CCW.

Gregory and Heard (1979) showed that the Café Wall illusion disappears if the luminance of the middle line is noticeably lower or higher than the luminance of the two types of squares (figure 5C). This is entirely consistent with our explanation that, in those configurations, the local line fragments alternately induce tilts in opposite directions and that this results in cancellation of the whole illusory tilt (figure 5D). Instructively, tilt is restored if the contrast polarity of every other line segment is reversed (figure 5E).

Furthermore, the reason why the Münsterberg illusion (figure 5F—Münsterberg 1897) renders a weaker tilt magnitude than the Café Wall illusion (figure 2A) is also suggested: As a consequence of being rendered in two rather than three gray-tones, there are only half the number of fragments (figure 5G), or elementary units, along its trajectory. Thus, qualitatively we expect a diminution of the illusory effect. We make no claim that the effect is exactly half—such a quantitative prediction would require more detailed computational or physiological models.

Finally, figures 5H–5J show the fragmented versions of the checkered illusion (figure 2B), the illusion of shifted gradations (figure 2C), and the illusion of striped cords (figure 2D), respectively. Again, each fragmented figure renders roughly the same tilt as the original.

4 New variations

Our method of graphical construction can also render four-tone stimuli—as illustrated in figures 6A–6H (and previewed in figures 2C and 2D). Figure 6A (the 'reverse Café Wall illusion') is a variation of the inert figure 5C which demonstrates that it is, in fact, possible to produce an effect (tilting CW) even if the luminance of the trajectory line lies wholly outside of the range of luminance modulated by the bricks—by alternating luminance along it from black to white. Figure 6B indicates which fragments of that line are important—the ones that correspond to 'tails' of our unitary elements. It also tilts CW.

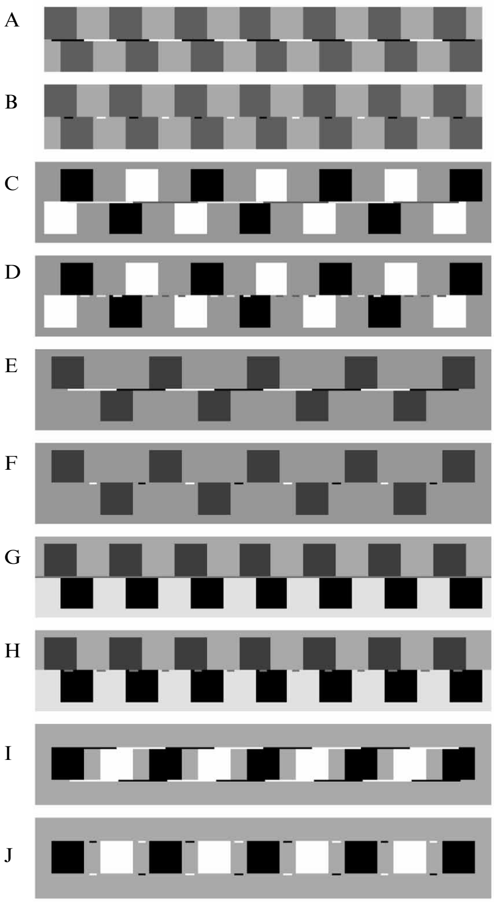

Figure 6. 'New' illusions produced by graphical construction. A and B, the 'reverse Café Wall illusion'; C and D, the 'Café Wall illusion of black and white squares'; E and F, the 'Café Wall illusion of separate squares'; G and H, the 'semi-Café Wall illusion'; I and J, the 'one-row Café Wall illusion'. The horizontal lines appear to tilt CW in A and B, and CCW in C–J. Note that fragments are placed near and in line with edges of squares.

Figure 6C (the 'Café Wall illusion of black and white squares') is a construction that counters another misconception—that the tilt effect requires the shifting of bricks of the *same* luminance (black, or white) so that they misalign by roughly half a brick's length. Here black bricks misalign with white ones, yet a CCW tilt is visible. Again, the corresponding elemental fragmented version is indicated in figure 6D. Indeed, figure 6E (the 'Cafe Wall illusion of separate squares') demonstrates that connected black or white bricks are not indispensable—here the striped trajectory line appears to tilt CCW. Figure 6F indicates the corresponding elemental version.

Figure 6G (the 'semi-Café Wall illusion') demonstrates that lightness changes do not unduly disturb the effect as long as they do not change contrast polarities of edges and line segments. The gray trajectory line continues to tilt CCW despite the reduction in contrast modulation in the upper row. Figure 6H indicates the corresponding elemental version.

Figure 6I (the 'one-row Café Wall illusion') demonstrates (in three tones) that tilts can be produced with only a single row of bricks. Here the upper and lower striped lines appear to tilt CCW. Figure 6J indicates the corresponding elemental version. Perhaps Café Wall variants traditionally employ two or more rows of bricks that generate the characteristic wedge effect, because it is easier to draw them that way.

5 Related illusions

Stimuli that contain many more than the four gray tones displayed in figure 6 can demonstrate similar tilt illusions. For example, figure 7A shows the 'Montalvo illusion' which contains a continuum of gray scales. First presented by Fanya S Montalvo in 1980 (Sakane 1980) it has since been termed the Lavatory Wall illusion (Woodhouse and Taylor 1987). Here a line is sandwiched between two rows of opposed sawtooth gratings and as a result its trajectory appears to tilt—CCW for a black line, and CW for a white one. This mimics the reversal of tilt direction with a reversal of contrast polarity seen in our elementary compositions. Indeed, such a composition emerges when quantising the sawtooth into discrete steps, eg into the five gray-tones seen in figure 7B. Figure 7C is a further variation where the elementary units have been rendered more explicitly simply by fragmenting the centre line into dark and light strips.

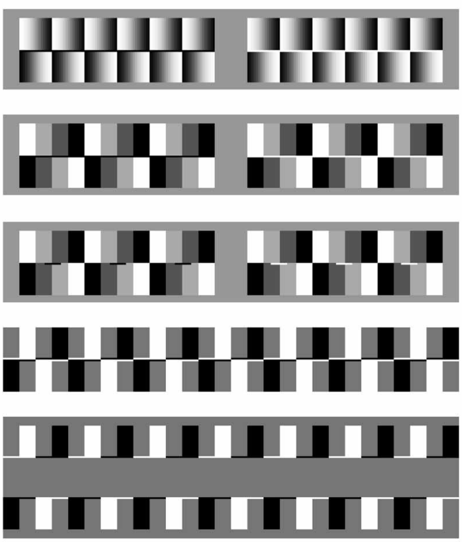

Figure 7. The 'Montalvo' illusion. A, sandwiched by sawtooth-wave gratings in opposite directions, a black line appears to tilt CCW, whereas a white line tilts CW; B, their quantised luminance-profile versions; C, fragmented versions of B; D, the Morgan – Moulden illusion, in which the middle line made up of double-deck, black and white line segments appears to tilt CCW; E, with the middle line sliced into the upper and lower parts, where both lines appear to tilt CCW, the Morgan – Moulden illusion can be attributed to our rules (figure 1).

Figure 7D shows the Morgan—Moulden illusion (figure 6 in Morgan and Moulden 1986), in which the middle line made up of double-deck, black and white line segments appears to tilt CCW. That this is indeed a construction of our unitary elements (see figure 4) is shown in figure 7E that slices into its upper and lower parts.

Other illusions, though visibly similar, are harder to conceive of as graphical constructions of unitary elements. Indeed, figure 8A (the illusion of 'shifted edges') is devoid of unitary elements, yet it exhibits a visible global tilt. Its illusory tilt (CCW), nevertheless, accords somewhat with our approach: it appears to isolate the complementary process whereby 'collector units' are alone at work transforming local tilt cues (here physically jagged edges) into global ones. Figure 8B (the illusion of 'fringed edges') is constructed from tiles that only approximate our unitary elements—in particular, each unit's tail has become a blob rather than a thin line. Figure 8C (the illusion of 'Y-junctions') shows a similar diminished tilt where the tail is now star-shaped.

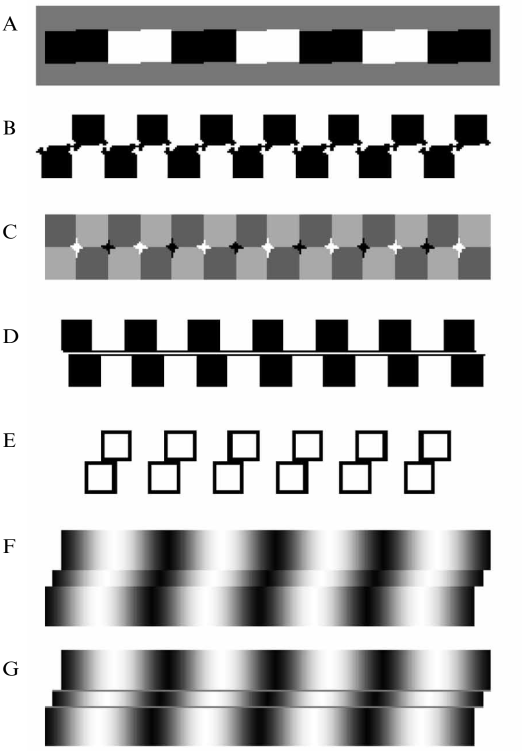

Figure 8. Illusions difficult to conceive as graph-
ical constructions: A, the illusion of shifted edges, in which the upper and lower horizontal edges appear to tilt CCW; B, the illusion of fringed edges, in which the middle horizontal edge appears to tilt CCW; C, the illusion of Y-junctions, in which the middle horizontal edge appears to tilt CCW; D, the illusion of shifted rows, in which the middle horizontal lines may appear to tilt CCW; E, the Hollow Squares illusion, in which middle horizontal lines appear to tilt CCW; F, the Haig illusion, in which the borders between shifted gratings appear to tilt CCW; G, if gray lines are added on the borders, the apparent tilt is reversed. This is the illusion of shifted gradations (figure 2C).

Since these blobs, or stars, occupy a coarser spatial scale than their thin-line counterparts, we expect their resultant trajectory lines to do so. The resultant tilts (both CCW) thus ought to be diminished, in accordance with the Gregory and Heard (1979) finding that the Café Wall magnitude diminishes as mortar lines thicken relative to brick height.

The remaining panels in figure 8 further explore the interplay between graphical constructability and spatial scale. Slicing the Münsterberg figure (figure 5F) into its upper and lower halves, as is shown in figure 8D (the illusion of 'shifted rows'), creates two new trajectories where previously there was but one. Both of the new trajectories are rendered inert at the fine scale, since along their lengths the graphical construction now alternates mutually canceling elements. Yet, a slight tilt (CCW) persists (though some report CW tilts). This may be explained at a coarser scale whereby the central bar gets resolved as a blurred gray bar—which then becomes amenable to graphical construction at that thicker scale. Again thicker tails mean a thicker trajectory and a weaker tilt. Incidentally, Bressan's (1995) alternative approach relates figure 8D to the structurally similar Hollow Squares illusion (figure 8F) first presented by Taylor and Woodhouse (1980). By definition, a hollow square cannot be constructed from our solid-colour unitary elements. Instead, we suggest that the perceived tilt could again be simply the activity of 'collector units' applied to the jagged corrugation of the fragmented centre line. Figure 8F, the Haig illusion (Haig 1989), contains—like figures 2C or 7A—shifted rows of gratings (here sinusoidal) and its tilt (CCW) can be explained in similar terms. Since the central grating is much thicker than a single line, we expect its resultant tilt to be weak (as it was for the case of figure 8D). Finally, figure 8H reintroduces fine-scale features into the Haig illusion by adding thin gray line borders between the gratings. As can be seen, in accordance with the rules of graphical construction a much stronger and reversed tilt now manifests itself obliterating the original Haig effect.

6 Discussion

By incorporating contrast polarity we have been able here to explain approximately four times as many phenomena as Helmholtz irradiation could alone (cf figure 1B) and twice the number of Kitaoka's corner effects (cf figures 1A and 1B). Furthermore, our empirical approach appears, at least in part, compatible with some existing mechanisms proposed to account for the emergence of local tilt cues, including both Gregory and Heard's border-locking model and Morgan and Moulden's bandpass filter theory.

The border-locking model pins down the perimeter between light/dark regions at their common boundary, attributing to large solid regions greater locking potential than that of thin lines. Gregory and Heard illustrated how local tilts might arise in Münsterberg and Café Wall figures due to the alternation of (strongly locking) solid region and (weakly locking) thin lines along their boundary trajectory—in much the same way as our elementary units alternate body and tail sections. However, since we count the mortar line as part of our units' tail, our approach differs significantly from that of Gregory and Heard (1979) who, rather inconclusively, consider it as simply a gap across which locking mechanisms may or may not compete. Border locking might perhaps be appropriate for the illusion of 'Y-junctions' (Kitaoka et al 2001) (figure 8C), or the Popple illusion (Popple and Levi 2000; Popple and Sagi 2000), which is generated by a series of phase-shifted Gabor patches.

Spatial filters offer an alternative mechanism involving simple models of visual receptive fields, including those in area V1 (Hubel and Wiesel 1962, 1968, 1977). With the aid of computers, such filters can be convolved with stimulus images, to simulate their ensemble responses. Indeed, Morgan and Moulden (1986) illustrated that a bandpass filter applied uniformly across a Café Wall type stimulus can reveal explicit local tilt cues where none is apparent: each mortar line becomes a twisted cord comprised of alternate thin dark–light off-horizontal segments, with each segment manifesting

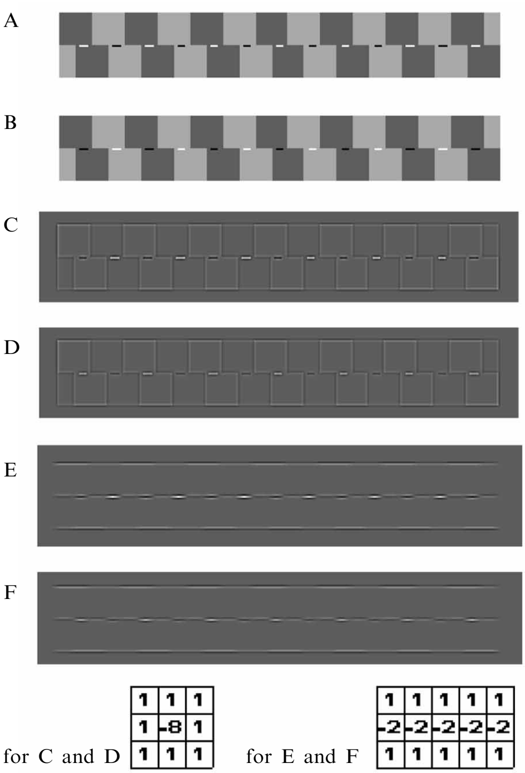

Figure 9. Bandpass filtering applied to A (corresponding to figures 1A and 1B) and B (corresponding to figures 1C and 1D; the same as figure 6B). A non-directional filter (lower-left inset) can generate twisted cords—C and D, respectively—but a directionally tuned filter (lower-right inset) does better, and is generally required—E and F, respectively. Filters are spatially tuned to the thickness of the mortar line in A and B—ie 1 pixel.

a measurable tilt indicative of perceived tilt. We computed similarly indicative twisted cords for the illusory images shown in this article—for example see figure 9. However, this required precise tuning of the bandpass filter, both spatially and directionally. In particular, a circular filter (a blob detector) did not reliably render twisted cords. Indeed, to achieve that, we needed to employ an elongated filter tuned to best respond to bars. These filters produced maximal responses only when oriented horizontally: ie along the true mortar line. Since this is not along the perceived trajectory, it seems that it is not the bandpass filters' orientations per se that signal perceived tilt but it could be their positions. In particular, this approach assumes that it is the (retinotopic) mapping of the positions of the maximally responding filters that generates the twisted cord pattern upon which collector units might act. In summary, such an explanation of illusion requires that our visual system overrides tilt cues occurring at earlier level of processing (be it retinal or cortical hypercolumn) with those extracted later from a second directional derivative image.

Given the continued speculative nature of the theories surrounding the nature of mechanisms that may produce the local tilt cue and those that may collect them together, our method of graphical construction of illusory stimuli from elementary units contributes a valuable heuristic tool.

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