Perception, 1994, volume 23, pages 691-708

The Hermann grid illusion: a tool for studying human perceptive field organization†

Lothar Spillmann
Neurologische Universitätsklinik mit Abteilung für Neurophysiologie, Hansastrasse 9, 79104 Freiburg, Germany
Received 17 August 1993, in revised form 31 January 1994

Abstract. Psychophysical research on the Hermann grid illusion is reviewed and possible neurophysiological mechanisms are discussed. The illusion is most plausibly explained by lateral inhibition within the concentric receptive fields of retinal and/or geniculate ganglion cells, with contributions by the binocular orientation-specific cortical cells. Results may be summarized as follows: (a) For a strong Hermann grid illusion to be seen bar width must be matched to the mean size of receptive-field centers at any given retinal eccentricity. (b) With the use of this rationale, the diameter of foveal perceptive-field centers (the psychophysical correlate of receptive-field centers) has been found to be in the order of 4-5 min arc and that of total fields (centers plus surrounds) 18 min arc. These small diameters explain why the illusion tends to be absent in foveal vision. (c) With increasing distance from the fovea, perceptive-field centers increase to 1.7 deg at 15 deg eccentricity and then to 3.4 deg at 60 deg eccentricity. This doubling in diameter agrees with the change in size of retinal receptive-field centers in the monkey. (d) The Hermann grid illusion is diminished with dark adaptation. This finding is consistent with the reduction of the center-surround antagonism in retinal receptive fields. (e) The illusion is also weakened when the grid is presented diagonally, which suggests a contribution by the orientation-sensitive cells in the lateral geniculate nucleus and visual cortex. (f) Strong induction effects, similar to the bright and dark spots in the Hermann grid illusion, may be elicited by grids made of various shades of grey; and by grids varying only in chroma or hue.

Not accounted for are: the illusory spots occurring in an outline grid ie with hollow squares, and the absence of an illusion when extra bars are added to the grid. Alternative explanations are discussed for the spurious lines connecting the illusory spots along the diagonals and the fuzzy dark bands traversing the rhombi in modified Hermann grids.

1 Introduction

The light or dark illusory spots perceived at the intersections of black or white bars are among the best-known examples of a simultaneous contrast illusion. The light spots were first noticed by one Reverend W Selwyn in the early 1840s and reported by Sir David Brewster in 1844 at a meeting in York (Brewster 1844). When a window with opaque dark bars was viewed against the bright sky, there was a whitish spot at the crossings. The luminous spots were brightest when not seen directly. The converse of this illusion, dark spots, was described (but not illustrated) by Ludimar Hermann in 1870, who saw them in a matrix of Chladni figures[(1)], in the translation of Tyndall's *Sound* (*Der Schall* 1869). In 1878, Hering discussed the illusion in his *Zur Lehre vom Lichtsinne* and in 1907 included two grids with opposite polarities in the Graefe-Saemisch Handbook of Ophthalmology (figures 29 and 30) showing the dark and

† Dedicated to Professor G Baumgartner, deceased 11 August 1991.

[(1)] Chladni figures are configurations produced when a horizontal metal plate, covered with lycopodium powder (or some other light powder), is set into vibration (eg by means of a violin bow or by light touch) while being held in one or more places to dampen the effect. The wiggly lines in each cell represent the lines of maximum vibration—the lycopodium has been displaced from these to the darker regions. It is not the Chladni figures that matter for the discovery of the Hermann grid illusion, but their fortuitous representation as white figures on a black background. For a reproduction see Wade (1978, his figure 7).

bright spots, respectively. The next to mention the illusory spots was Prandtl (1927), followed by Ehrenstein (1941, 1954) and Dombrowsky (1942). Wade (1978, 1982) and Hood and Petry (unpublished manuscript) have traced the history of this intriguing phenomenon that has become popular not only in visual science, but also in op art (Vasarely 1965, 1974a, 1974b; Bode 1972; Wade 1982).

This article summarizes research on the Hermann grid illusion over the last 30 years since Baumgartner (1960, 1961) first proposed an explanation in terms of the antagonistic center-surround organization of circular receptive fields. During this period a host of papers have been published in an attempt to test and challenge Baumgartner's hypothesis. What have we learned from these studies about the Hermann grid illusion? And what is its value as a tool for probing the human visual brain?

2 The Hermann grid illusion

In figure 1a an example of the Hermann grid illusion is shown. In this grid the intersections of the white bars look less bright (actually pale grey) and those of the black bars look less dark (actually dark grey) than the bars themselves, even though the luminance of the bars is uniform. In the tradition of Mach (1865), Hermann (1870) attributed the illusory spots to simultaneous contrast. Anticipating the idea of a center-surround receptive field (Kuffler 1953) by eighty years, he wrote:

> "An explanation of this phenomenon by simultaneous contrast is easy. The apparent brightness of each point on the white grid depends on the amount of black which exists in a certain area around it. If one assumes the diameter of this area to be larger than the width of the white stripes, then each point on the intersections *receives in its surround less black* than any other point on the white stripes; its brightness will thus be less enhanced by contrast and must therefore appear darker." [Hermann (1870); translation and italics by the author]

Hering (1920) also attributed the grid illusion to simultaneous contrast. However, he accounted for the illusory spots in terms of more white rather than of less black in the surround:

> "At any intersection of two white stripes, seen indirectly and with normal eye movements, a very washed-out grey spot appears because this place *is much more completely surrounded by equally intense parts* than any other equally large area of the white stripes." [Hering (1920) quoted from the translation by Hurvich and Jameson (1964); italics by the author]

From these two quotations one might conclude that it is not so much the darkening at the intersection which is peculiar, but rather the enhanced brightness of the bars. The dark spot at the intersection would merely be the consequence of less simultaneous contrast present in this location. An analogous explanation had already been suggested by Brewster (1844) for light illusory spots. The assumption of a relative depression of brightness or darkness at the intersection, due to less contrast, is consistent with modern accounts of these phenomena.

In addition to the illusory spots at the intersection one also observes a narrow dark canal running the full length of a bar, with bright edges flanking it on either side. These phenomena have been attributed to inner and border contrast (Dombrowsky 1942). Small eye movements in conjunction with afterimages, proposed by later investigators as possible causes of the Hermann grid illusion (eg Tschermak 1929; Ehrenstein 1941, 1954; Verheyen 1961; Sindermann and Pieper 1965), are not sufficient for an explanation since the illusory dark spots are visible at very brief exposure durations (Spillmann 1971). This was already known to Hering when he wrote:

> "Still even with fixation, in the first few seconds after the figure is presented, the effect is noticeable in the parts of the figure seen indirectly and to this extent belongs with the phenomena of *pure simultaneous contrast*. When I placed the figure in direct sunlight and

exposed it only for 1/40 sec, I was able to perceive the grey spots in indirect vision" [Hering (1920) quoted from the translation by Hurvich and Jameson (1964); italics by the author]

Thus, although eye movements are not needed to elicit the Hermann grid phenomenon, the temporal transients produced by freely viewing the stimulus pattern may sustain and actually enhance the illusion. With steady fixation, the Hermann grid illusion

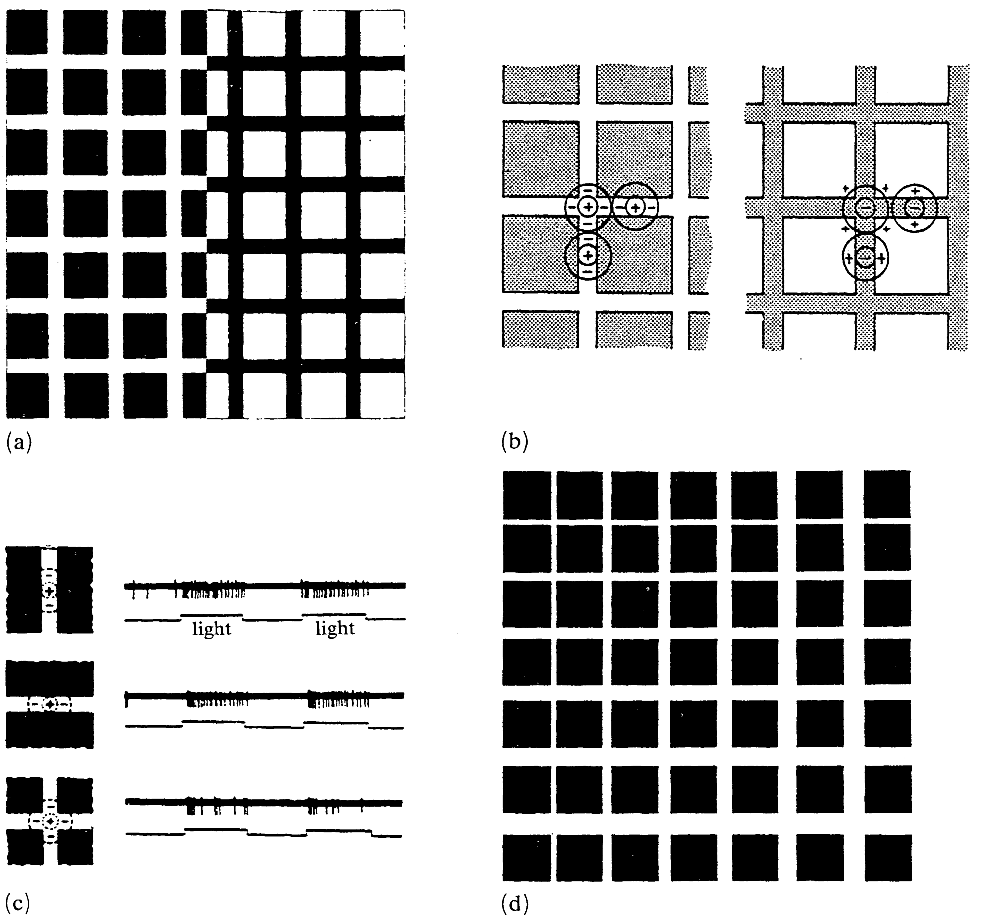


Figure 1. (a) Hermann grid illusion (Hermann 1870). Dark spots appear at the intersections of the white grid (left) and light spots at the intersections of the black grid (right). The recommended observation distance for this (and the other figures in this paper) is 0.5 m. Note that the illusion is greatly reduced in strength, if not absent, in foveal vision. (After Hering 1907.) (b) Baumgartner's (1960) explanation of the Hermann grid illusion, illustrating how receptive fields of on-center (left) and off-center (right) neurons might be illuminated to account for the illusory spots at the intersection. The darkening results from increased lateral inhibition, the brightening from reduced lateral activation. '+' denotes excitation, '−' denotes inhibition. (From Spillmann 1971.) (c) Discharge pattern of a cortical cell with a concentric receptive field (first order B neuron of layer 4c in Area 17 of the cat; data from Schepelmann et al 1967). The neuronal firing rate is about the same for the vertical and the horizontal bars, but is reduced to half when both bars are presented together. (From Jung and Spillmann 1970.) (d) Hermann grid with increasing bar width. The grid illustrates the effect of increasing size of perceptive-field centers with retinal eccentricity. If one fixates at the upper left corner, so that the narrowest crossing falls on the fovea and the wide ones fall on the periphery, dark spots are perceived at most intersections, including the foveal one. If, however, one fixates at the lower right, so that the widest crossing falls, inappropriately, on the fovea, the dark spots are absent from the foveal region. (From von Helversen 1965; see also Frisby 1979.)

quickly diminishes and disappears because of local adaptation. It is not visible in the negative afterimage following flash exposure of the stimulus pattern (Spillmann 1971).

Today, the most commonly accepted explanation of the Hermann grid illusion is that suggested by Baumgartner (1960), which is based on the receptive-field organization of the human visual system. In Baumgartner's model (figure 1b, left), brightness signalling on-center cells stimulated by the intersection receive about twice as much lateral inhibition as cells stimulated by the bars. As a result, the intersection appears darker. Conversely, in a black grid on a white background, darkness-signalling off-center cells stimulated by the intersection receive only about half as much lateral activation as cells stimulated by the bars (figure 1b, right). Thus, the intersection appears lighter.

Although on-center and off-center cells may both contribute to the perceived brightness of each kind of intersection, recent accounts by Wässle et al (1983) and Schiller (1992) of the structural and functional segregation of these two neuronal subsystems suggest a largely independent processing of white and black grids. Perceptually, the dark and bright spots are not exactly equivalent: When presented with patterns of either polarity (such as figure 1a), subjects report the illusory darkenings more often than the illusory brightenings (Spillmann and Levine 1971). A similar asymmetry has also been reported for the Ehrenstein illusion (Spillmann et al 1984).

Schepelmann et al (1967) tested the receptive-field explanation of the Hermann grid illusion by recording impulses from individual fibers in the optic nerve and from single cells in the lateral geniculate nucleus and visual cortex of the cat. They found a neuronal response pattern consistent with the illusion for cells at all three levels, including simple cells. In figure 1c the response of a nonorientation selective cortical neuron is shown. The firing rate is about the same for the vertical and horizontal bars, but is much reduced when both bars are presented together, intersecting each other. This reduction of the firing rate might be considered a neurophysiological correlate of the perceived darkening; it is consistent with Baumgartner's receptive-field explanation of the Hermann grid illusion.

Although the different-firing-rate explanation of the dark and bright illusory spots is attractive, the assumption that perceived brightness is proportional to the neuronal discharge pattern at some locus in the visual pathway may be oversimplified, and in the case of some brightness illusions is demonstrably false (see Uttal 1978, 1981). Moreover, local brightness is most likely perceived not through the activity of just a few individual cells (Barlow 1972, 1985; Teller 1980), but through the interaction of many neurons. To explain the Hermann grid illusion more adequately, one should, therefore, take into account the spatial distribution of neural activity arising from the illumination of overlapping receptive fields (Spillmann and Levine 1971; Spillmann et al 1987; see also section 6).

There is, however, a problem. Although the intersection should look darker than the bars (as indeed it does), it should also look considerably lighter than the background. This is because the net excitation of neurons stimulated by the grid should be higher than that resulting from diffuse stimulation by the surround. Yet, an enhancement of the brightness of the intersection above that of the white surround is not reported (Laming 1992). Rather, the intersections look the same as the surround or even appear darker. This problem could perhaps be resolved in terms of current models of brightness coding (Watt and Morgan 1985; Kingdom and Moulden 1992) in which it is assumed that the uniform region surrounding the grid appears white (and not grey), because it is determined by the convolution response of operators (bandpass filters) at the edge of that region. This response is interpreted as signalling a step change in brightness which continues unabated (ie nonisomorphic) across the uniform region. The perceived darkening, on the other hand, is in line with the results of a nulling experiment by Troscianko (1982b) who found that, relative to the threshold on a uniform field, a luminance increment of up to 1.2 log units had to be superimposed onto the intersection to cancel the illusory dark spot (for comparison see Monjé 1955; Payne and Anderson 1969). This result is reminiscent of center–surround interaction in the Westheimer paradigm (Westheimer 1967; Spillmann et al 1987) and is consistent with the assumption of lateral inhibition being the main cause of the Hermann grid illusion.

3 Perceptive-field measurements

Baumgartner (1960) hypothesized that the illusory spots are strongest when the bar width corresponds to the diameter of the receptive-field center. Under this condition the lateral inhibition at the intersection, relative to that at the bar, should be maximum. With wider or narrower bars, the difference in net excitation between neurons stimulated by the interaction or by the bar should decrease, resulting either in a weaker, or in no illusion. Ultimately, the illusion should break down (Spillmann 1971, figure 4).

If this assumption holds, the Hermann grid illusion can be used as a tool to determine, psychophysically, the size of human perceptive-field centers. A perceptive field is the psychophysical correlate of single-cell receptive fields and is defined as the functional 'entrance cone' for a number of neurons at some level of the visual system. The size of this neural aperture is given by the retinal area within which interaction (spatial summation, inhibition) between stimuli takes place. In analogy with receptive fields, the perceptive field is assumed to have a center and an antagonistic surround and to overlap with other perceptive fields.

Assuming linearity, a perceptive field could be defined as the point-spread function of an operator derived from psychophysics as opposed to neurophysiology (Watt 1988). Typically, perceptive fields in human observers are assessed with ocular fixation allowing for some jitter of the stimulus on the retina, whereas receptive fields of single cells are measured in anesthetized animals whose eye muscles have been paralyzed. It is difficult to tell whether this difference in retinal image stabilization should affect the comparison between receptive and perceptive fields. However, inasmuch as in both cases the stimuli are transient, by virtue either of short exposure duration or of frequent retinal displacement, their effect on the visual system might be expected to be similar or the same.

To determine the size of perceptive-field centers, the observation distance (and thus the visual angle of the inducing stimulus) is varied until the illusion is maximal. For a threshold measurement it is assumed that the critical bar width at which the illusory spots are strongest corresponds to the size of the perceptive-field center.

3.1 *Perceptive-field centers*

Using this rationale, Baumgartner (1960) and Spillmann (1964) obtained values of approximately 4–5 min arc for foveal field centers (about 20μ). This small value explains why the illusory spots tend to disappear when viewed foveally. The reason is that the grids used for demonstrating the illusion typically are far too wide, ie receptive fields are stimulated to approximately the same extent regardless of whether they are illuminated by the bar or by the intersection. When the mismatch is resolved by the use of narrower bars appropriate to the size of foveal field centers, the illusory spots will also be seen in central vision. Hermann (1870) had already suggested:

> "The fact that the darkening is absent on intersections which are fixated, may be explained by the assumption that for objects imaged on the central retina, the surrounding area, within which simultaneous contrast can become effective, is smaller than for other retinal regions." [Hermann (1870); translation by the author]

Troscianko (1982b) has argued that the values measured in this way may represent an underestimation. He pointed out that the illusory spot extends slightly beyond the intersection onto the bars. Center size should therefore be 1.4 (ie the square root of two) times the bar width. Even so, center diameters in the fovea would only be 6 – 7 min arc, which is in good agreement with the peak frequency (4 – 5 cycles deg^{-1}) of the spatial-contrast-sensitivity function (Robson 1966).

Significantly, amblyopes require wider intersections [up to 23 min arc (Meur et al 1968)] to perceive the darkenings. This would suggest that the perceptive-field centers in amblyopes' (pseudo) foveae are similar in size to the perifoveal perceptive-field centers of normal subjects, in accordance with amblyopes' reduced visual acuity.

3.2 *Fovea versus periphery*

Using the Hermann grid illusion one can determine the size of human perceptive-field centers, not only in the fovea but also in the periphery (Spillmann 1964). This is done by displacing the fixation point along the horizontal meridian and viewing a given intersection at peripheral locations of 15, 30, 45, and 60 deg. Such measurements cannot be very precise as they are based merely on a qualitative criterion. A method in which nulling, brightness matches, or increment thresholds are used might be more convincing. However, even so, subjects are reasonably confident in judging whether or not an illusion is present and whether it is weak, medium, or strong. Results based on such judgments show that perceptive-field center size increases from the fovea towards the periphery. Specifically, critical bar width increases steeply from a foveal value of 4.5 min arc to 1.7 deg at 15 deg eccentricity and then doubles to 3.4 deg at 60 deg eccentricity (Kornhuber and Spillmann 1964; Jung and Spillmann 1970). White and black grids yield similar values.

This increase in size of perceptive-field centers with increasing retinal eccentricity correlates well with the rate of increase of neurophysiologically determined receptive-field centers recorded from single cells both in the spider and in the rhesus monkeys (Hubel and Wiesel 1960; DeMonasterio and Gouras 1975). It is also in agreement with independent psychophysical measurements of the size of perceptive-field centers derived from Westheimer functions in human observers (Ransom-Hogg and Spillmann 1980) and in trained rhesus monkeys (Oehler 1985; Spillmann et al 1987).

The progression in perceptive-field center size from fovea to periphery may be visualized by inspection of figure 1d. If one looks at the narrowest crossing, in the upper left corner, the illusion is present at most intersections including the foveal one. But if one looks at the widest intersection (lower right corner), a dark spot is perceived at most peripheral locations, but is completely absent from the foveal region. This observation is in agreement with the finding by Sindermann and Deecke (1970) that there is a wide range of acceptable bar widths in the Hermann grid illusion (eg 0.5 – 4 deg at an eccentricity of 5.6 deg), and is consistent with a broad distribution of receptive-field sizes postulated for each retinal location (Koenderink 1977; Wilson and Bergen 1979). The bar width of which the Hermann grid illusion is strongest most likely reflects median center size (Troscianko 1982b).

3.3 *Perceptive fields*

The Hermann grid illusion may not only be used to measure the size of perceptive-field centers, but also of perceptive fields (centers plus surrounds). This is done by determining the bar width at which the illusion disappears, ie when the difference in net excitation between those neurons illuminated by the intersection, and those neurons illuminated by the bar falls below threshold. Using this rationale, Spillmann (1971) obtained a diameter of 18 min arc for foveal perceptive fields. Similar values were found by gradually increasing the length of the intersecting bars until the illusion was maximal (Ronchi and Salvi 1965; Spillmann 1971). These findings compare well with a field size of 17 min arc derived from the Westheimer function (Westheimer 1967; Enoch et al 1970).

Given a perceptive-field center of 4.5 min arc, the obtained field sizes yield a center-surround ratio of 1:4. Ronchi and Salvi (1965) further reported an oscillatory increase and decrease of the strength of the illusion with increasing bar length. This dependence may be due to multiple annular zones surrounding the physiological receptive field and producing periodically recurring disinhibition (Hammond 1973).

4 Retinal versus cortical origin?

Other factors, such as flicker rate, dark adaptation, and binocularity, have also been studied in the Hermann grid to isolate the neural mechanisms underlying the illusion. The results are as follows. First, the illusion is enhanced by stroboscopic illumination (4-15 flashes s^{-1}). This finding would be expected if temporal transients were essential for producing the illusion or if lateral inhibition and apparent contrast were enhanced by intermittent stimulation (Kitterle and Corwin 1979; Coren et al 1988). Second, the Hermann grid illusion becomes weaker and ultimately breaks down with dark adaptation (Wist 1976; Savardi and Saviolo 1982; Troscianko 1982b). This observation is consistent with the finding that under scotopic illumination lateral inhibition in the retina is reduced and finally abolished. This loss of inhibition is evidenced by the disappearance of the center-surround antagonism in retinal receptive fields (Barlow et al 1957; Maffei and Fiorentini 1972). Third, the illusion becomes weaker, or is absent, both with dichoptic and with stereoscopic presentation (Uttal and Matheson 1971; Uttal 1973; Lavin and Costall 1978; Troscianko 1982a; Brookes and Stevens 1989). These results point towards a predominantly monocular origin of the effect, presumably in the retina.

However, the evidence is not clear. Reliable observations with dichoptic and stereoscopic stimulation are difficult to obtain because of binocular rivalry (Spillmann 1971) and may actually depend on the stimulus configuration used. Julesz (1965, 1971 his figure 2.7-3) reported a strong brightness change at the intersections of a binocularly fused random-dot grid where the horizontal bars appeared in front of the vertical bars. Since the two monocular half-images did not exhibit the illusion, it must have originated in the binocular neurons of the cortex. Wist (1974) similarly showed that the Hermann grid illusion could be perceived on a hollow grid (eg without solid squares) presented in front of the background.

Further evidence for a postretinal contribution comes from the fact that the Hermann grid illusion is weakened when the grid is presented diagonally (Spillmann 1971; Spillmann and Levine 1971). This 'oblique effect' (Appelle 1972) indicates an influence of orientation-sensitive cells in the lateral geniculate nucleus (Vidyasagar and Urbas 1982) or, more likely, in the primary visual cortex (Hubel and Wiesel 1962). Finally, the Hermann grid illusion is perceived in isoluminant colored grids, varying only in chroma or hue (McCarter 1979; Levine et al 1980; Oehler and Spillmann 1981). This finding is consistent with the suggestion that under these conditions the illusion is mediated by the double-opponent cells or Type III cells of the lateral geniculate nucleus and striate cortex (Wiesel and Hubel 1966; Hubel and Wiesel 1968; Gouras 1974).

Structural features, such as spatial arrangement, have also been found to influence the Hermann grid phenomenon. For example, Wolfe (1984) observed that the illusion becomes stronger with an increase in number (1 versus 4 versus 9 etc) of orderly arranged intersections. There was no increase in strength when the intersections were placed irregularly (ie each in isolation). These results cannot be attributed to local differences in lateral inhibition or activation. They are suggestive, rather, of the involvement of global mechanisms, in addition to local perceptive fields. A similar thought has also been entertained by Troscianko (1983). Thus, although it appears appropriate to assume a retinal and/or geniculate origin for the Hermann grid illusion, a more central contribution is needed to account for the effects found with depth, orientation, color, and grouping in modified Hermann grids.

5 Brightness and color induction

To further probe the nature and origin of the Hermann grid illusion, it was studied under various psychophysical stimulus conditions. In one such study (Spillmann and Levine 1971) the effect of figure-ground contrast was investigated. It was found that, in accordance with the relatively low saturation level of contrast-mediating cortical neurons (Campbell and Maffei 1970), the Hermann grid illusion does not require high contrast between figure and ground. Instead it is seen at nearly full strength down to figure-ground ratios of 0.5 log unit before it becomes weaker.

Moreover, the two intersecting bars need not have the same contrast with respect to the background. In a modified Hermann grid, consisting of bars of various shades of grey, the reflectance of the upper bar must lie between the reflectances of the background and the lower bar. For example, bright illusory patches are most salient on light-grey bars intersecting black bars on a white background, whereas dark patches are seen best on dark-grey bars intersecting white bars on a black background (Spillmann and Levine 1971, their figure 1a; see also White 1979, 1981; Massironi and Sambin 1984). This finding is in agreement with Baumgartner's (1960) receptive-field model which predicts a lightening in the first case and a darkening in the latter.

However, unlike the regular Hermann grid illusion, the bright and dark patches in such patterns can easily be seen foveally, they are well defined, perceptually stable and, thus, may be a phenomenon of their own different from the more diffuse and fleeting appearance of the illusory spots in the Hermann grid. Also, in foveal vision the patches occur for a wide range of bar widths up to 80 min arc (about 0.4 cycles deg^{-1}), many times the diameter of foveal perceptive-field centers found with the regular Hermann grid (Spillmann and Levine 1971, their figure 9). It therefore appears that these phenomena are related to the brightness-induction effects occurring in sinusoidal grating patterns (McCourt 1982; Foley and McCourt 1985). When a uniform horizontal stripe is superimposed on such a grating, its brightness changes in counterphase: the stripe looks brighter on dark bars and darker on bright bars. Like the Hermann grid illusion, grating induction is mostly a low-pass phenomenon, both spatially and temporally (upper cutoffs at 5 cycles deg^{-1} and 10 Hz, respectively), and is enhanced by flicker (Anstis 1993). It saturates at a contrast of about 30% (McCourt and Blakeslee 1994; see also Spillmann and Levine 1971) and grows weaker with dark adaptation (McCourt 1990). Although induced brightness persists in dichoptic vision, suggesting an origin at the level of the striate cortex, it does not depend on the orientation of the inducing stimuli (McCourt 1982). The induced gratings can mask real gratings just as effectively as can real gratings—however, only at low spatial frequencies (Kingdom and McCourt 1993).

Chromatic induction effects may also be observed. In modified Hermann grids varying only in chroma or hue, Oehler and Spillmann (1981) perceived the strongest effects of heterochromatic intersections, where the colored bars crossing each other did not have the same hue (for a demonstration see their figure 1). To obtain an optimal effect the overlying stripe had to be similar or equal in hue to the background, whereas the underlying stripe had to be maximally different. For example, a typical heterochromatic intersection might consist of a yellow-red bar intersecting a blue-green bar on a red background. The resulting illusory patches are characterized by an increase of chroma and/or a hue shift, usually away from the color of the underlying stripe. In isochromatic grids the illusion was quite weak.

When a grey grid is presented on a colored (eg red) background, the illusory spots are also tinged with the background color (Preyer 1897/98; Prandtl 1927; Dombrowsky 1942; Segal 1957). This change in appearance of the intersection towards the color of the background is analogous to the brightness change observed in the achromatic Hermann grid illusion. Similarly, a narrow red line resembling inner contrast can be seen extending along the middle of the white bars (Prandtl 1927).

6 Computational models

In addition to neurophysiological mechanisms, computational models have been proposed to predict hypothetical mechanisms of visual processing, which can be assessed by empirical findings. With regard to the Hermann grid illusion, models have made use of the center-surround antagonism (lateral inhibition) in early visual processing (Frisby 1979). In accordance with Baumgartner's (1960) model, a difference-of-Gaussians or a Laplacian-of-Gaussian model (eg Marr 1982; Watt 1988) with different weights of center and surround shows the predicted result. In the case of the white intersections, the raised lateral inhibition produces a local depression of brightness resulting in the illusory dark spot. For the black intersections, all signs are reversed. The finding that critical bar width increases from fovea to periphery and that in each location there is an upper and lower limit for the appearance of the illusion is suggestive of spatial-frequency-selective processing with different receptive-field sizes being involved.

Grossberg and Todorovic (1988, their figure 26) have advanced a brightness-computation model which is based on the on-brightness channel alone. Their computational approach yields a distribution of relative brightness which is similar to the one predicted by Baumgartner's model. They proposed an architectural framework of two interacting visual subsystems dedicated to control processing ('Boundary Contour System') and to featural filling in ('Feature Contour System'), respectively. Both subsystems are activated by cells with concentric center-surround receptive fields, so that the distributed activity generated by the early stages is fed into the regional compartments of the orientationally selective system in the cortex (Grossberg and Mingolla 1985).

7 Open questions

The Hermann grids described so far consist of bars of uniform width, intersecting each other at right angles. However, grids with other properties have also been tested. In figure 2a a grid that elicits the illusion even more strongly than Hermann's (1870) original pattern is shown. This grid was obtained by rounding off the corners in a regular Hermann grid, producing large diamond-shaped intersections (Dombrowsky 1942). In this grid, dark spots surrounded by a bright halo are perceived at the intersections. The illusory spots are most conspicuous with eye movements. They are severely diminished when the pattern is presented diagonally, suggesting a central origin.

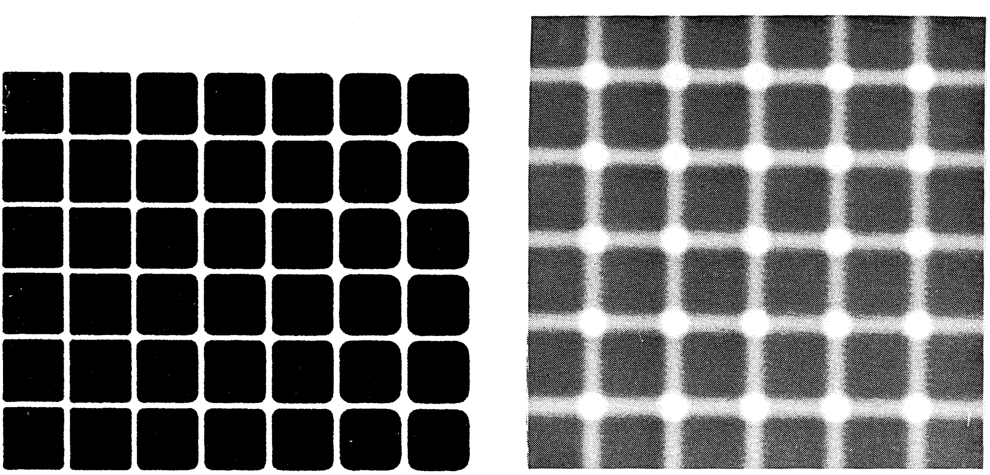
Bergen (1985) demonstrated that the dark spots occur even when the surrounding bars are of lower contrast (figure 2b). For a pattern, he first blurred a regular Hermann grid and then increased the luminance at the intersections relative to the luminance of the bars. The resulting dark spots perceived in the middle of the white disks are perplexing because they occur in an area whose luminance is actually greater than that of the surrounding bars. The presence of the disks may be crucial. When a regular Hermann grid is blurred by viewing it through a sheet of onion paper the illusion is not strengthened, but rather abolished (Dombrowsky 1942). This observation is also unexpected because removal of the high spatial frequencies is generally assumed to enhance simultaneous-contrast phenomena (ie *flor* contrast).

A further challenge may be found in figure 3a (lower right corner). Here, dark illusory spots continue to be seen although the solid black squares of the Hermann grid have been replaced by squares of decreasing contrast and finally by mere outlines of squares (Horemis 1970; Spillmann 1977; Wade 1982, his figure 1.6.2). These spots are quite small and are surrounded by a thin bright annulus similar to that seen in figure 2a. As in the previous grids, the spots tend to disappear with rotation of the grid by 45°. Berbaum and Chung (1981) proposed that receptive fields with very small centers and a narrower-than-normal inhibitory surround might account for these darkenings, since they would maximize the difference in neuronal response between cells stimulated by the intersection and the bar, respectively. There is a peculiar reversal in appearance of this illusion. When figure 3a is observed from a greater distance, the illusory spots change from small dark spots to diffuse bright spots.

Curiously, when the intersection of a Hermann grid is delineated by a square-shaped contour (figure 3b, left), the illusory darkness spreads uniformly within the entire intersection (Jung 1973). This effect persists even in foveal vision and when the grid is presented diagonally. No such darkening is perceived in a hollow control grid (figure 3b, right).

One might ask whether the Hermann grid illusion depends on bars which are collinear and intersecting each other at right angles. In figure 3c a grid where the upper and lower halves of a bar have been laterally displaced by increasing amounts relative to each other is shown. As a result the illusory spots become progressively weaker, presumably because the difference in net excitation dcreases due to the offset. Only the dark canals mentioned in section 2 remain.

In contrast with lateral displacement, when one of the bars is rotated through an angle of about 30°, the illusion remains largely unaffected (figure 3d). However, there may be limits. For a qualitative inspection, the reader is referred to the op artist Vasarely (1965, 1974a, 1974b) who has produced a variety of patterns which show these and other stimulus modifications in black and white as well as in color (see Wade 1978, his figures 9 and 10).



(a) (b)

Figure 2. (a) The pin-cushion-like darkenings at the intersections of this rounded grid are stronger than the dark spots in the regular Hermann grid. Note the decrease in strength of the illusion when the grid is rotated by 45°. (After Dombrowsky 1942 and Bergen 1985.) (b) Dark scintillating spots may be seen on these intersections in this example, in which the intersections have a higher luminance than the bars. (From Bergen 1985, with permission.)

In an effort to test for additivity of contrast effects, Lingelbach et al (1985) combined a Hermann grid with an Ehrenstein figure (Ehrenstein 1954) by adding four diagonal bars to the intersection. They predicted that the dark illusory spots should become more pronounced because of the extra lateral inhibition. However, in figure 4a the illusion largely disappears showing that this is not the case. If anything, there is a diffuse brightening with a small dark spot in the center. No account for this effect has been given suggesting that it would warrant a more systematic investigation (eg bar width, angle, number of extra bars). There are further examples that are difficult to reconcile with the simple explanation provided by circular perceptive fields.

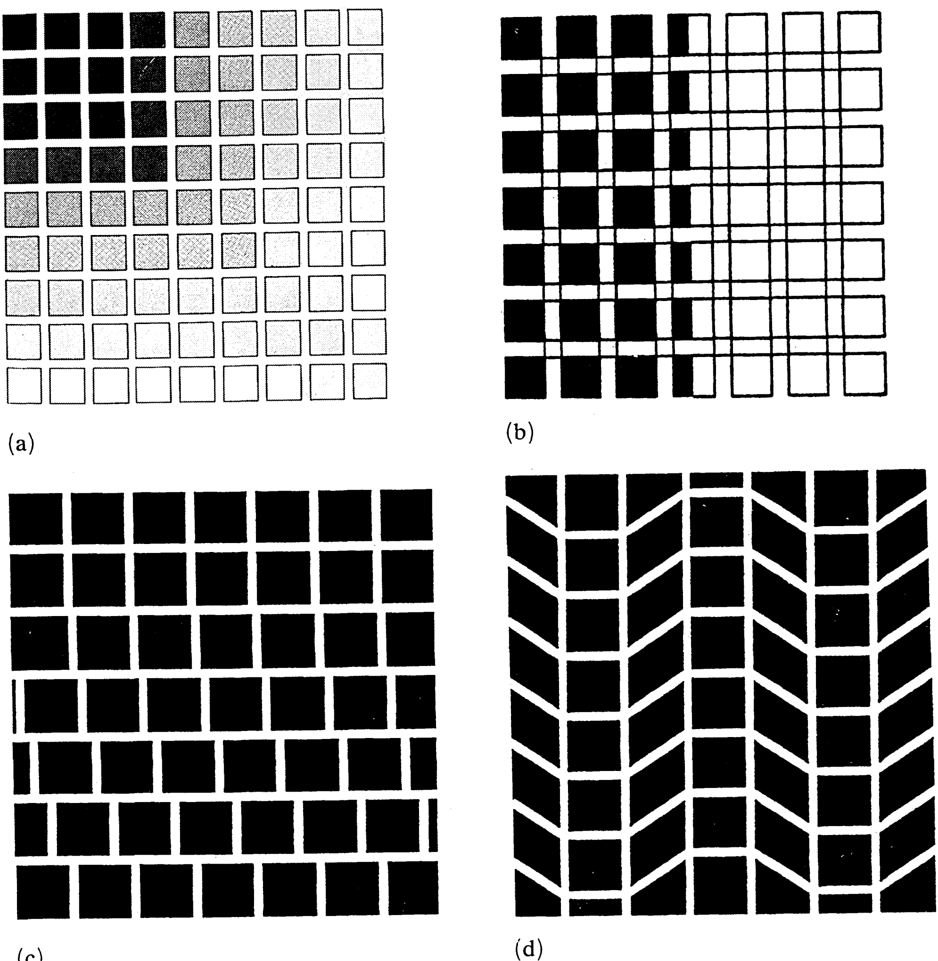


Figure 3. (a) Hermann grid with squares of decreasing contrast. The illusion gradually weakens, but does not disappear even in the outline grid. Note that the illusory spots change in size from large to small with decreasing contrast. (From Horemis 1970.) (b) When the illusory area of a regular Hermann grid is delineated by a square the enclosed area is seen as uniformly darker, even in central vision (left half). No such darkening is observed in a hollow grid presented as a control. Note, however, the fine bright dots at the crossover points of the delineating lines in the right half of the figure. (After Jung 1973.) (c) A step-like offset of intersecting bars weakens, but does not abolish, the Hermann grid illusion. (d) The Hermann grid illusion persists despite angular rotation of one of the bars.

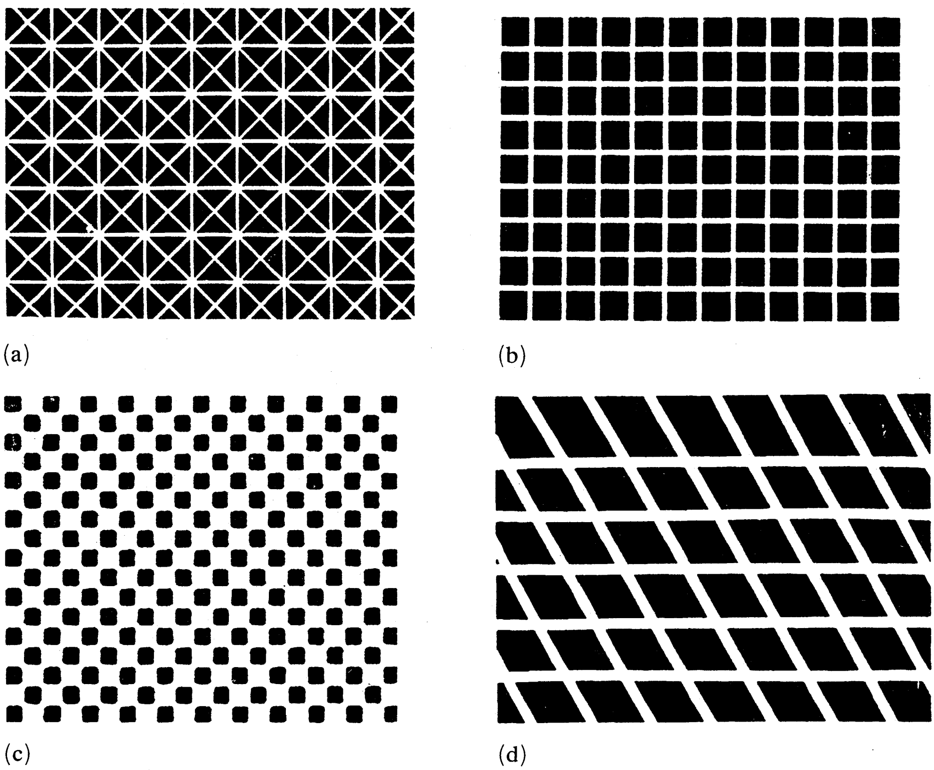


Figure 4. (a) When four diagonal bars are added to the Hermann grid, the illusion is all but gone. There is only a weak darkening with a brighter halo around it. (From Lingelbach et al 1985.) (b) A regular lattice of thin dark lines appears to connect the illusory spots along the diagonals. Spots and lines can both be seen foveally. (From Prandtl 1927.) (c) This figure may be conceived as a Hermann grid where each second square has been omitted. Faint grey diagonal lines may be seen passing through the white spaces. (From Lindsay and Norman 1977.) (d) In this grid, diffuse dark bands appear to cross the black rhombi along their short axes. The strength, clarity, and width of these bands depend on the angle of intersection. (After Motokawa 1950.)

8 Prandtl and Motokawa grids

In 1927 Prandtl pointed out that in a Hermann grid composed of small black squares, a lattice of dark spurious lines could be seen passing diagonally through the squares and connecting the illusory spots at the intersections. This effect is shown in figure 4b. Prandtl reported that, unlike the dark spots in the Hermann grid illusion which are diminished, these lines were enhanced in clarity, when the grid was rotated by 45°. Schachar (1976) observed similar lines in a pincushion grid (a Hermann grid with the bars becoming narrower at the intersections). He concluded that the thin lines could not be predicted from the two-dimensional Fourier transform, since there was no diagonal component in the laser-produced diffraction pattern. These claims were followed by immediate rebuttals (Boulter 1977; Ginsburg and Campbell 1977; Rudee 1977), insisting that Fourier analysis and spatial frequency filtering can indeed account for the phenomenon (see the debate in *Science*: Schachar et al 1977; Boulter 1977; Ginsburg and Campbell 1977; Rudee 1977; Ochs 1979). Prandtl's lines have also been reported in colored pincushion grids (McLeod 1978).

Figure 4c resembles a small-sized Hermann grid with alternating black squares omitted. In this figure, faint grey lines are seen criss-crossing the pattern along the diagonals ("Springer lines": Lindsay and Norman 1977, their figure 1-42). To explain the effect, Morgan and Hotopf (1989) proposed that there must be some superordinate neuronal assembly sensitive to individual Fourier components. These so-called "collector units" are assumed to combine the outputs of local orientation-sensitive detectors from different field positions and in this way generate the illusory diagonal lines.

Laming (1992), on the other hand, attributed the illusory lines to an internal pattern of neuronal activity resulting from the recombined outputs of a number of Fourier channels after certain nearthreshold and subthreshold components have been selectively compressed. The 'defective' transmission of signals resulting from this compression would lead to the perception of the fuzzy lines in Prandtl patterns and would explain the illusory spots in the Hermann grid. Laming emphasized that these illusions are not isomorphisms of the patterns of neural activity at some level of the sensory pathway as Baumgartner (1960, 1988, 1990) assumed for the Hermann grid; rather the information implicit in the neural patterns is interpreted in terms of the physical stimuli which would have produced them. He noted, however, that the dark diagonal bars in the Hermann grid (figure 4b) cannot be explained by the compression of any set of Fourier components.

Similar considerations apply to the diffuse dark bands bisecting the black rhombi in figure 4d along their minor axes. In these distorted Hermann grids, the inducing bars cross each other at other than right angles. An angle of 32° was found to be optimal (Ronchi and Bottai 1964; Ronchi and Salvi 1965). Grids of this kind were originally investigated by Motokawa (1950, 1970) who discussed them in terms of "retinal induction". Visual Fourier analysis has been advanced as an alternative explanation by Psotka (1977) and Sambin (1979).

9 Resumé

Future research on the Hermann grid illusion and related illusions might concentrate on measuring illusory strength by the use of increment thresholds, cancellation, and brightness matches in the region of brightness change. Also, in view of Baumgartner's (1960) explanation of the Hermann grid illusion and its close correlation with the neuronal firing pattern in the cat, one would expect that cats and monkeys should perceive the illusory spots and bands in a way similar to humans. This needs to be shown in a behavioral experiment.

If visual perception were always veridical (ie linear), we might never discover how it really works. Illusions are indicative of some nonlinearity in the processing system. They are an essential and noninvasive tool for testing our understanding of perception against our better knowledge of the visual world. Next to Mach bands (von Békésy 1960; Baumgartner 1964), the study of the Hermann grid illusion has perhaps contributed the most to a better understanding of the correlations between human brightness perception and the underlying perceptive-field organization. Studying it has been enjoyable and very worthwhile indeed.

Acknowledgments. This work was, in part, supported by Deutsche Forschungsgemeinschaft, SFB 325, Teilprojekt B4. J Cornelissen devised figures 3c and 3d, and B Lingelbach made figure 4a available. W Ehrenstein kindly provided a copy of Dombrowsky's dissertation. D Laming, M McCourt, and N J Wade contributed greatly to the discussion. N J Wade drew the author's attention to the original reports on the grid illusion by Selwyn and Brewster, and J Mollon provided the letter by Preyer. B Dresp, W Ehrenstein, and H Neumann commented on an earlier draft of the manuscript. S Menees improved the English. I thank them all.

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