Perception, 2010, volume 39, pages 1565 – 1578

doi:10.1068/p6539

Capturing lightness between contours

Mark Vergeer, Rob van Lier
Donders Institute for Brain, Cognition and Behaviour, Centre for Cognition, Radboud University Nijmegen, PO Box 9104, 6500 HE Nijmegen, The Netherlands; e-mail: m.vergeer@donders.ru.nl
Received 3 August 2009, in revised form 20 November 2010; published online 13 January 2011

Abstract. Homogeneously coloured bars may exhibit lightness differences at the intersections. A well-known example is the Hermann grid illusion, where crossing white bars on a black background show dark patches at the crossings. Jung (1973, *Handbook of Sensory Physiology* volume VII/3, pp 1 – 152) found that the dark patches persist when thin outlines are drawn at the intersections, and are even visible in foveal vision. Recently, it has been shown that making distortions to the contours of a Hermann grid-like configuration results in the disappearance of the illusory dark spots (Geier et al, 2008 *Perception* **37** 651 – 665). We show that thin outlines at the crossings of the distorted Hermann grid induce lightness differences in the same direction as in the original Hermann grid illusion, even in foveal vision and in displays consisting of two crossing bars. Our experiments reveal that the induced lightness differences are independent of the luminance polarity and shape of the contours at the intersection. We suggest that the effect results from lateral inhibition and an additional spreading and capturing of these differences between luminance contours. A similar capturing between collinear contours may play a role in peripheral vision in the original Hermann grid.

1 Introduction

Uniformly coloured crossing bars may exhibit lightness differences at their intersections. A typical example is the Hermann grid illusion (1870), perhaps one of the best-known illusions in vision science. The classical demonstration consists of black squares separated by white horizontal and vertical bars, on which dark spots are perceived at the intersections (see figure 1a). The effect is strong in the periphery of the visual field, but nearly absent in foveal vision. In the past decades, the Hermann grid illusion has led to various accounts concerning the underlying mechanisms.

The earlier literature on the Hermann grid attributed the illusion to simultaneous lightness contrast (eg Hering 1874/1964; Hermann 1870); specifically, the perceived dark spots were explained by less contrast at the intersections, since the intersections are surrounded by less black than the bars. Following this argument, one may say

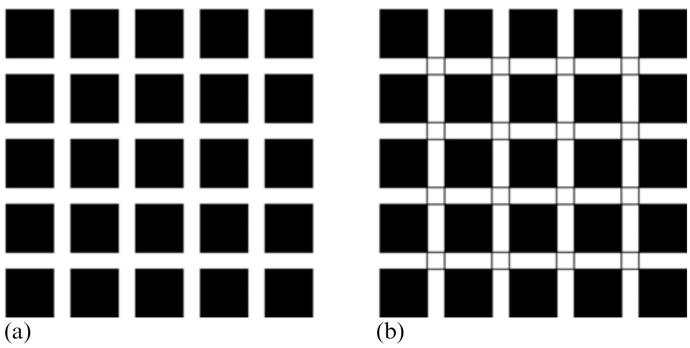


Figure 1. A traditional Hermann grid is presented (a), while on the right (b) thin contours have been drawn delineating the central squares after Jung (1973) and Spillmann (1994). As a result of these outlines, the dark spots that are perceived in a traditional Hermann grid are even present in foveal vision.

that the perceived spots are not so much the result of a darkening at the intersection, but are mainly the result of a brightening at the non-intersecting parts of the bars (Spillmann 1994). Baumgartner (1960) explained the Hermann grid effect in terms of the receptive field organisation of retinal ganglion cells. This explanation has since then dominated the textbooks. Because of the antagonistic centre/surround structure of retinal receptive fields (eg Kuffler 1953; Spillmann 1994; Werblin and Dowling 1969), 'on-centre' cells respond strongly to stimulation at the receptive field centre, but are inhibited by stimulation of the surround (lateral inhibition). Since the surrounds of the receptive fields at the intersections of a Hermann grid receive more light than the surrounds at non-intersecting parts of the bars, these cells are inhibited more strongly, resulting in less brightness (ie the perceived dark spots at the intersections of the grid). The absence of the effect in the fovea could be explained by the fact that foveal receptive fields are much smaller than receptive fields in the periphery. As a result, there is no difference in lateral inhibition between receptive fields stimulated by the intersection and the bar, respectively.

The retinal ganglion cell hypothesis can account for the perceived dark spots in the Hermann grid. Nevertheless, several studies have demonstrated that this hypothesis is not sufficient to explain the Hermann grid illusion to its full extent, and it has been suggested more than once that cortical mechanisms also play a role in the effect (eg Geier et al 2008; Lingelbach et al 1985; Schiller and Carvey 2005; Spillmann 1994). For instance, when diagonal bars are added to the original Hermann grid, the illusion should become stronger as a result of increased centre/surround antagonism at the intersections of the bars. This is not what happens—if anything, the effect is diminished (Lingelbach et al 1985). Schiller and Carvey proposed an alternative theory with an important role for S1 type simple cells in the primary visual cortex which respond to the grid.

In the present study, two earlier observations regarding the Hermann grid stand out. First, it was reported that extending the contours of a traditional Hermann grid across the intersections "does not destroy the illusion" (Jung 1973, page 47; Spillmann 1994). Figure 1b clearly shows that the intersections are perceived as uniformly darker (in a white grid on a dark background), even in foveal vision. In addition, it has been shown that presenting horizontal and vertical bars that differ in luminance (with one of the bars on top of the other at each intersection) produces lightness effects in foveal vision (Hamburger and Shapiro 2009; Spillmann and Levine 1971). In both cases the luminance contours surrounding the central squares cause the lightness effect to be captured at the intersection.

Recently, Baumgartner's hypothesis has been challenged by Geier et al (2004, 2008), who showed that making simple distortions to the grid abolishes the original effect. In figure 2, we show that, when delineating the interaction of a Geier-like distorted grid with thin contours, the dark patches will reappear. The phenomenon in figures 1b and 2b suggests that the outline-induced lightness difference is not specific to the Hermann grid as the darkening is also visible in foveal vision. Nevertheless, it may reveal a mechanism that also underlies the original Hermann grid illusion.

The above observation that extending the contours across the intersections of crossing bars leads to lightness differences does not apply only to Hermann grid-like configurations, as the effect can already be observed when viewing a single crossing. In the following experiments, we therefore focus on such single crossings of homogeneously coloured bars with the aim of testing both the observed direction of the lightness differences and the effects of contour curvature at the intersection areas. In the first experiment, we demonstrate that the lightness effect proceeds regardless of the luminance polarity of the contours. In the second experiment, we demonstrate that the differential lightness is captured by the contours surrounding the intersections,

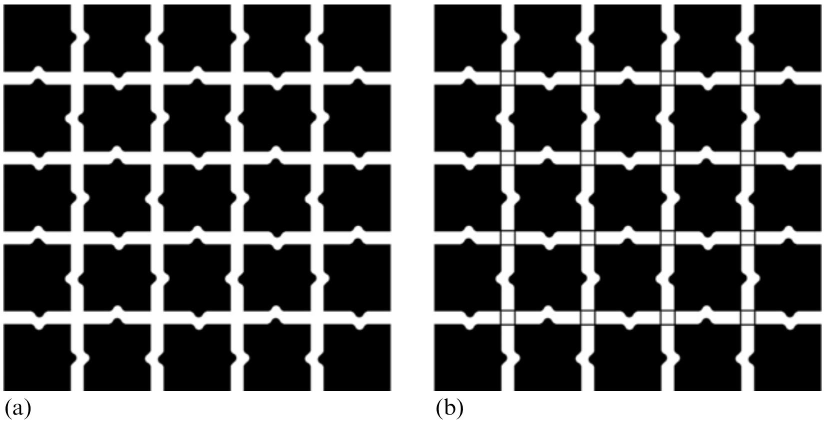


Figure 2. (a) A Geier-like modification of the Hermann grid which greatly reduces the visibility of the dark spots. (b) Drawing Jung-like contours at the intersections results in reappearance of the dots, even in foveal vision, just as in figure 1a.

irrespective of the shape of these contours. Furthermore, we curved the contours around the intersection to investigate whether the shape of the area at which differential lightness is perceived is determined by the shape of the contours. We then discuss and test whether these findings also hold for distorted grids.

2 Experiment 1

2.1 *Method*

2.1.1 *Participants.* Ten undergraduate students participated in this experiment (age 20–27 years, mean age 24.0 years). All had normal or corrected-to-normal vision and none of them had knowledge of the experimental hypothesis. Observers received course credits for participation.

2.1.2 *Stimuli and design.* In this experiment, we focus on a single crossing of the grid. As already mentioned, the effect we are reporting occurs not only in the periphery, but also in foveal vision. During stimulus presentation, participants could freely focus at the crossing of the grid. The stimuli used comprised a cross, consisting of a horizontal and a vertical bar (length: 34.5 cm; visual angle: 17.8 deg; width: 2.1 cm; visual angle: 1.09 deg). Stimuli varied on the following factors. Contours: luminance of the background (L_{bg}), luminance of the cross (L_{cross}), and luminance of the contours ($L_{contour}$). These factors had the following levels. Contours: the bars either had no contours (figure 3a), contours around both bars, except at the intersection (figure 3b), contours only at the intersection (figure 3c), or contours around the bars, and extended across the intersection (figure 3d). Luminance: L_{bg} light (39.22 cd m^{-2}) or dark (11.01 cd m^{-2});

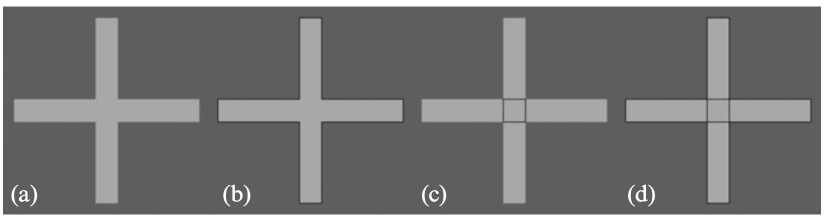


Figure 3. The contour settings used in experiment 1. The different panels show the four conditions: (a) no contours around the bars; (b) contours around the bars, but not extended across the intersection; (c) contours only around the intersection; and (d) contours around the bars and extended across the intersection. The area at the intersection of the bars started with a random luminance and was adjusted by the participants until its lightness matched the lightness of the rest of the two bars.

L_{cross}: light (32.32 cd m^{-2}) or dark (16.54 cd m^{-2}); and $L_{contour}$: white (99.99 cd m^{-2}) or black (0.00 cd m^{-2}). The contours were 0.07 cm (0.04 deg) thick. Each of the 32 unique trials ($4 \times 2 \times 2 \times 2$) was repeated four times, which led to a total of 128 trials, preceded by 4 practice trials.

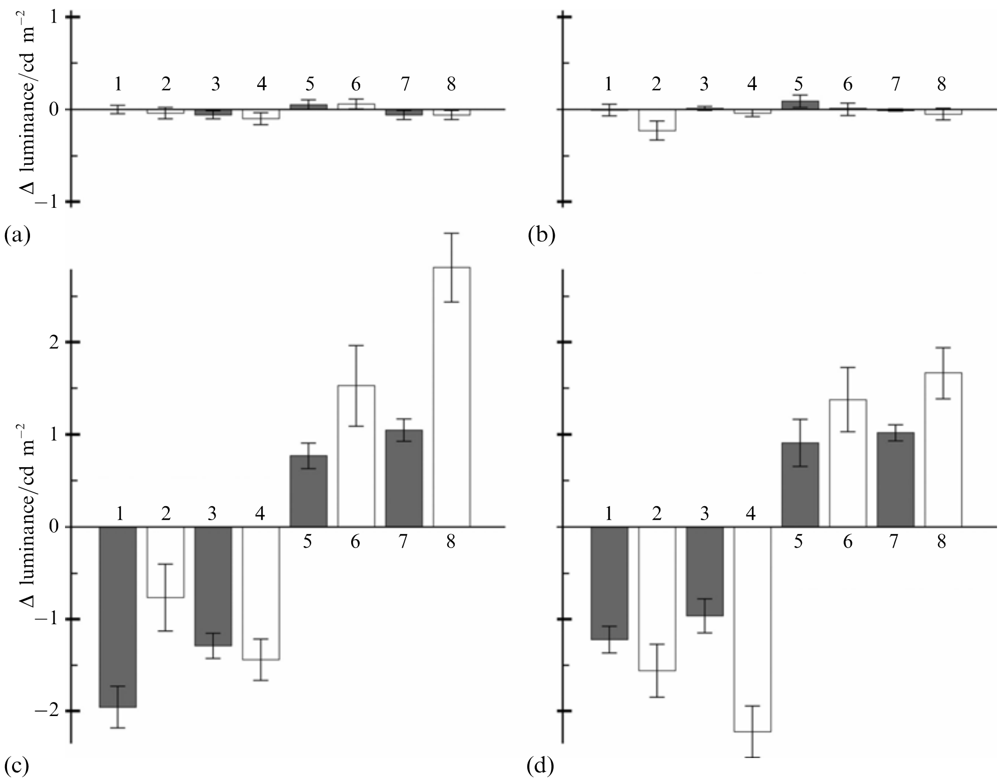
The experiment was run on a PC Pentium-III configuration, and stimuli were presented on a 19-inch CRT monitor. The viewing distance was 110 cm. Colorshop 2.6/monitor optimiser (X-Rite) was used for monitor calibration and colour measurements.

2.1.3 *Procedure.* In each trial, the luminance of the central square area started at a random grey value (corresponding to RGB values between 0 and 255). Participants adjusted the grey value of the crossing until its lightness was the same as the lightness of the remaining parts of the bars. This grey value could be varied in steps of -10, -1, $+1$, or $+10$, with each option corresponding to a key on a standard keyboard. When the participant was satisfied by the match, he/she pressed the space bar to continue with the next trial. There was no time limit for the task.

2.2 *Results*
We calculated the mean differences between the grey value of the bars and the grey value of the central square after matching. The analyses were performed on these grey values. For all conditions, mean effects in terms of luminance are presented in figure 4. The results refer to the conditions in which no contours were presented (figure 4a), contours were presented around the bars but not at the intersection (figure 4b), around the intersection (figure 4c), and around the bars as well as the intersection (figure 4d). As can be seen in figures 4a and 4b, and supported by t-tests, none of the conditions in which the contours were absent at the intersection yielded significant lightness differences. Therefore, we analysed only the conditions in which contours were presented around the central area (intersection) of the cross (levels 3 and 4 of the factor contours, corresponding to figures 4c and 4d, respectively). An ANOVA revealed a significant effect of L_{bg} ($F_{1,9} = 349$, $p < 0.001$); when the cross was brighter than the background, the centre square appeared darker than the rest of the cross, and vice versa. This interaction confirms our initial observations in figure 2. Significant interactions were obtained for $L_{bg} \times L_{cross}$ ($F_{1,9} = 5.13$, $p < 0.05$), contours $\times L_{contour}$ ($F_{1,9} = 22.4$, $p < 0.005$), $L_{bg} \times L_{contour}$ ($F_{1,9} = 28.2$, $p < 0.001$), and for $L_{bg} \times L_{cross} \times L_{contour}$ ($F_{1,9} = 17.0$, $p < 0.005$).

We now focus on the effects found for the conditions in figures 4c and 4d. These figures show that, in all conditions in which the luminance of the background was higher than the luminance of the cross, the area inside the contour was perceived as lighter than the remainder of the cross. This was the case both for dark and for light contours presented around the central area. The effect was significant for all conditions ($t_9 > 5.05$, $p < 0.005$), with the exception of condition 2 in figure 4c ($t_9 = 2.082$, $p = 0.067$). Conversely, in all conditions in which the background was darker than the cross, the area inside the cross was perceived as darker than the rest of the cross ($t_9 > 3.46$, $p < 0.01$). These results show that the direction of the lightness effect is not influenced by the luminance of the contours. However, it seems that the magnitude of the effect in either direction is larger when a white contour is presented around the crossing as compared to a black contour, as is reflected by the significant interaction $L_{bg} \times L_{contour}$.

2.3 *Discussion*
The results of experiment 1 show that no lightness effects were perceived when no contours were presented around the intersection. This is in accordance with what is known about the original Hermann grid, namely that the effect does not occur in foveal vision. Note that for these conditions the adjustment task was relatively easy because of the edges formed by local luminance differences between the centre and



(1) Light background, light cross, black contours
(2) Light background, light cross, white contours
(3) Light background, dark cross, black contours
(4) Light background, dark cross, white contours
(5) Dark background, light cross, black contours
(6) Dark background, light cross, white contours
(7) Dark background, dark cross, black contours
(8) Dark background, dark cross, white contours

Figure 4. Results of experiment 1. The columns show, for each condition, the mean luminance difference between the arms of the cross and the intersection of the cross after adjustment by the participants. In the upper two panels, results are shown for the condition in which no luminance contours were presented (a) and when contours were presented around the cross, but not at the intersection (b). The lower two panels show the results when luminance contours were presented around the intersection of the horizontal and the vertical bar (c) and when luminance contours were presented around both the horizontal and the vertical bar as well as the intersection of the two bars (d).

the rest of the bars. The conditions with contours presented around the intersection are more interesting. Both the effect of the background luminance as found in the ANOVA and in the *t*-tests reveal lightness effects in each separate condition. When the cross had a higher luminance than the background, the area at the intersection was perceived as darker than the rest of the cross, as indicated by a matching response in the opposite direction. More importantly, the effect does not depend on the polarity of the contour luminance. In comparison, when a dark-grey cross was presented on a light-grey background, the direction of the effect was reversed, ie the intersections were perceived as lighter. Again, the effect does not depend on the luminance polarity of the presented contours. Note that this effect rules out an account of assimilation by means of which the colour of the outlines would 'bleed' into bars.

Furthermore, the 2-way interaction between the background luminance (L_{bg}) on the one hand and the luminance of the contours ($L_{contour}$) on the other hand showed that the magnitudes of the effect are in general larger for a white contour than for a black contour. This could perhaps be due to a difference in relative luminance settings for the contours and the grid between conditions. A light cross presented on a light background is the only stimulus for which the magnitude of the effect was larger in the black-contour condition.

All in all, the results show that, whereas the direction of the lightness induction is independent of the luminance polarity of the contour, the induction does depend on the luminance of the bars as compared to the luminance of the background. To further illustrate this, in figure 5 we have once again displayed four cross configurations [(a), (b), (e), (f)], where the luminance of the bars is always the same. The luminance of the background is either higher [(a) and (b)] or lower [(e) and (f)] than the luminance of the bars, and the contours are either white [(a) and (e)] or black [(b) and (f)]. The two central panels [(c), (d)] display the same squares as those at the intersections of the crosses, on a background that equals the luminance of the cross configurations in the other panels. In agreement with the results of experiment 1, the central squares in (a) and (b) appear slightly lighter than in the rest of the bars, whereas they appear slightly darker in (e) and (f). Possibly the lightness appearance of the central squares may be modulated by the luminance of the outline of the square [(c) and (d)].

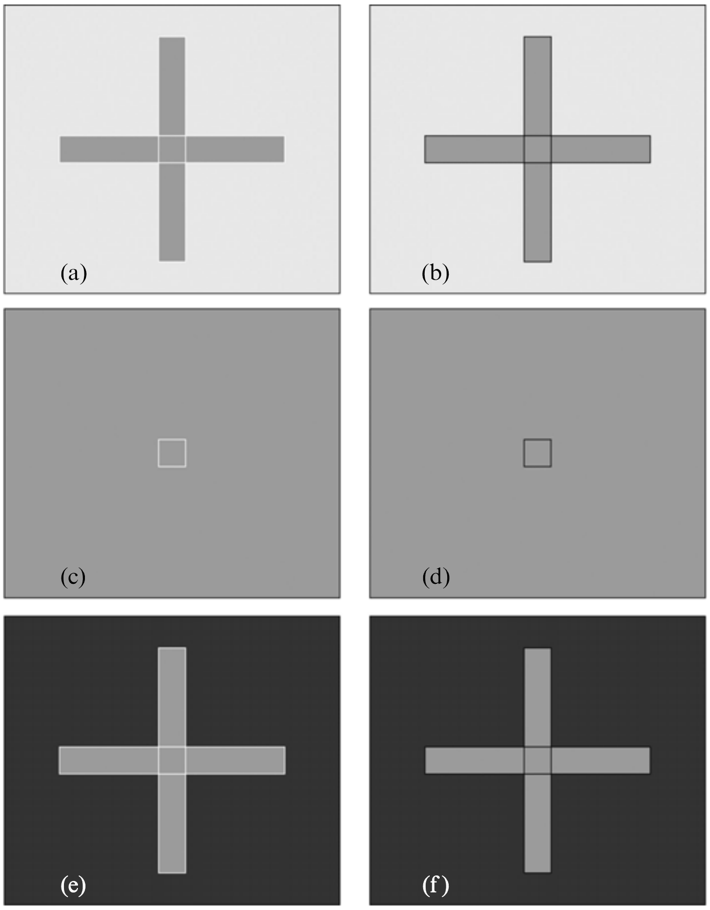


Figure 5. In (a), (b), (e), and (f) the luminance of the central squares is the same as the luminance of the rest of the bars, and differs from the luminance of the grey background. In (c) and (d), the central squares are presented on a uniformly coloured grey background, identical to the luminance of the bars in (a), (b), (e), and (f). Note that the direction of the lightness effect in the central square in (a), (b), (e), and (f) does not depend on the luminance of contours but, instead, on the luminance polarity of the bars versus the background.

However, this could not explain the effects in the cross configurations, since the direction of these effects vary depending on the luminance relations between the cross and the background. We argue that induced lightness differences due to lateral inhibition spread within the outlined bars, but are blocked by the outlines, regardless of the luminance polarity of these outlines. As a result, different lightness is perceived at the bars than in the centre of the cross.

3 Experiment 2

The results of experiment 1 suggest that the perceived lightness effects at the intersections are captured by the contours delineating the intersections, which is confirmed by the result of experiment 1. In experiment 2 we investigate whether the capturing of lightness occurs regardless of the shape of the contours. Specifically, we manipulate the shape of the contour at an intersection of a single crossing.

3.1 *Method*

3.1.1 *Participants.* Ten healthy undergraduate students participated in this experiment (age 20 – 28 years, mean age 23.4 years). All had normal or corrected-to-normal vision and were naive regarding the experimental hypothesis. Observers received course credits for participation.

3.1.2 *Stimuli and material.* As in experiment 1, stimuli consisted of crosses made of intersecting bars (bars had a length of 34.5 cm (ie 17.8 deg), and a width of 2.1 cm (ie 1.09 deg). The horizontal bar, including its contour, was always straight, while the vertical bar and its contour could either be straight (as in the stimuli in experiment 1) or have small indentations as in the example in figure 6 (the contours of the bars had a width of 0.07 cm, ie 0.04 deg). In half of the trials mirror images (about the vertical axis) were presented. As in experiment 1, two luminance levels were used for the cross and the background, with either a dark cross ($L = 16.54$ cd m^{-2}) presented on a light background ($L = 39.22$ cd m^{-2}), or vice versa. In each trial, either black ($L = 0.00$ cd m^{-2}) or white ($L = 99.9$ cd m^{-2}) contours were presented surrounding the horizontal and vertical bars and continuing in the central area. Thus, the crosses were always luminance increments on dark backgrounds or luminance decrements on light backgrounds. The intersection of the cross (the central area) had a luminance which was either slightly lower than, equal to, or slightly higher than the luminance of

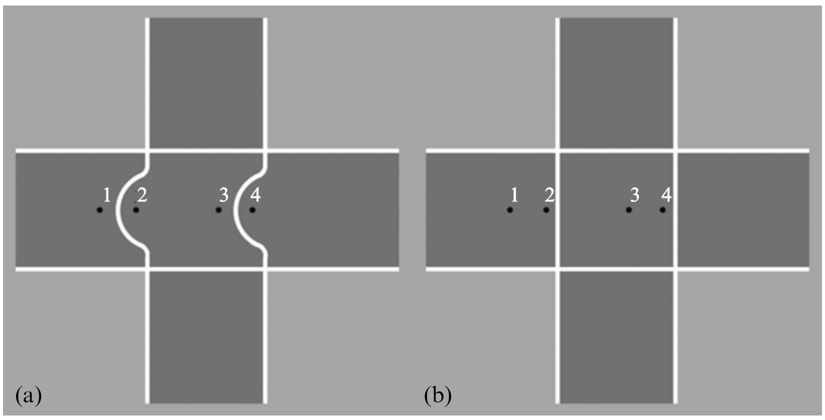


Figure 6. In each trial of experiment 2, two of the four dots in this figure were superimposed on the cross configuration. Subjects judged which of the areas immediately surrounding the two dots appeared lighter. Notice that in the curved-contour condition (a) dot 2 was located inside the outlined area, while in the straight-contour condition (b) this dot was located outside the outlined area. For dot 4, the opposite was true.

the remainder of the cross: in the case of a dark cross on a light background, the central area had a luminance of 15.90, 16.54, or 17.19 cd m^{-2}; conversely, when a light cross was presented on a dark background, the central area had a luminance of 38.19, 39.22, or 40.26 cd m^{-2}. The viewing distance was 110 cm and the experimental setup was the same as in the previous experiment.

3.1.3 *Procedure.* In each trial, two small black dots were presented at different locations on the cross. The four possible dot locations are indicated as 1, 2, 3, and 4 in figure 6. The task for the observers was to compare the lightness of the areas immediately surrounding the two dots, and to indicate which of these areas appeared lighter (a similar procedure was followed in van Lier 2002). In figure 6, dots 1 and 4 are positioned outside the delineated intersection, whereas dots 2 and 3 are positioned inside the delineated area. In each trial, one of the following comparisons had to be made with respect to the lightness of the immediate surroundings of the dots: 1 with 2, 3 with 4, 1 with 3, or 2 with 4. For the configuration with straight contours, only comparisons between the area surrounding dot 2 and dot 4 had to be made. After a response was given (either "left" or "right"), the next configuration appeared on the screen. Each of the configurations was presented 4 times, which led to a total of 240 trials. These trials were preceded by 4 practice trials and were presented in a randomised fashion.

3.2 *Results*

We were interested in the trials in which the delineated area had the same luminance as the remainder of the cross. Therefore, we will present the results of these trials only. We start with analysing the perceived lightness differences of the areas surrounding dot 2 and dot 4. Notice that for the curved-contour conditions the relation between the dots and the contours is reversed compared to the straight-contour conditions (see figure 6). The results of this comparison for both the straight-contour and the curved-contour conditions are presented in figure 7.

As can be seen in figure 7, in each luminance condition there are large differences in lightness effects depending on the shape of the contours. Let us first focus on the conditions with a dark cross on a light background. In most curved-contour trials,

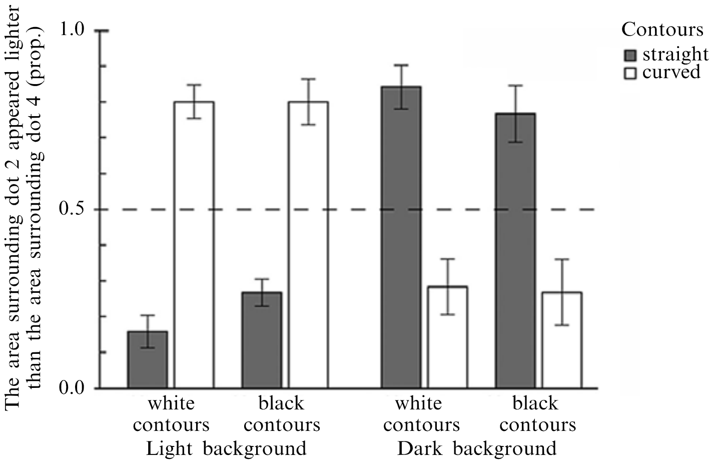


Figure 7. The results of comparisons between the areas immediately surrounding dot 2 and dot 4 as defined in figure 6 for both the curved-contour and the straight-contour conditions. As can be seen, the results are rather similar for the white-contour and the black-contour conditions. In the conditions with a dark cross presented on a light background, the area immediately surrounding dot 2 appeared lighter than the area surrounding dot 4, and vice versa for the condition with a light cross presented on a dark background.

the area surrounding dot 2 appeared lighter than the rest of the cross. This was the case both for the trials with white contours ($t_9 = 6.194$, $p < 0.001$) and with black contours ($t_9 = 4.630$, $p < 0.005$). In the same luminance conditions, but with straight instead of curved contours, the effect was reversed, with the area surrounding dot 4 now being perceived as lighter than the area surrounding dot 2. Again, effects were significant for both white contours ($t_9 = 7.235$, $p < 0.001$), and black contours ($t_9 = 6.983$, $p < 0.001$). In the other luminance condition, with a light-grey cross presented on a dark background, the pattern of results was reversed. In most curved-contour trials, the area surrounding dot 4 (outside the outlined area) was perceived as lighter than the area surrounding dot 2 inside the outlined area ($t_9 = 2.751$, $p < 0.05$ and $t_9 = 2.492$, $p < 0.05$ for white and black contours, respectively). Just as in the 'dark cross' conditions, the effects were reversed in the conditions with straight contours. The area surrounding dot 2 now appeared lighter than the area surrounding dot 4, both for white contours ($t_9 = 5.452$, $p < 0.001$) and for black contours ($t_9 = 3.320$, $p < 0.01$). To summarise: for all conditions in which a dark cross was presented on a light background, the results show that the area surrounding the dot lying inside the outlined area was perceived as being lighter than the area surrounding the dot lying outside the outlined area. On the other hand, all conditions in which a light cross was presented on a dark background show a reversed pattern of results, with the area surrounding the dot inside the outlined area being perceived as darker than the area surrounding the dot outside the outlined area. This effect is independent of the shape and luminance of the contours used in this experiment.

The results of the other comparisons (curved-contour conditions; dot 1 with dot 2, dot 1 with dot 3, and dot 3 with dot 4) are generally consistent with the previously described results. The overall pattern is that when a dark cross was presented on a light background, the area surrounding the dot inside the outlined area appeared lighter than the area surrounding the dot outside the outlined area. This was the case for all comparisons in the white-contour condition ($t_9 > 6.19$, $p < 0.001$), and for the comparison between dot 3 and dot 4 in the black-contour condition ($t_9 = 2.69$, $p < 0.05$). The comparison between dot 1 and dot 2 and between dot 1 and dot 3 did not reveal a significant effect in the black-contour condition. When a light cross was presented on a dark background the general pattern was that the area surrounding the dot inside the outlined area was perceived as darker than the area surrounding the dot outside the outlined area. Again, this was the case for all comparisons in the white-contour condition ($t_9 = 2.59$, $p < 0.05$), and for the comparison between dot 1 and dot 2 ($t_9 = 3.52$, $p < 0.01$) and between dot 1 and dot 3 ($t_9 = 2.88$, $p < 0.05$) in the black-contour condition. The comparison between dot 3 and dot 4 in the black-contour condition was marginally significant ($t_9 = 2.29$, $p < 0.051$).

3.3 *Discussion*

As in experiment 1, the effect of experiment 2 occurs for a light-grey grid on a dark-grey background and vice versa. Furthermore, again the direction of the effect is independent of the polarity of the contours (black or white). To conclude: the results of experiment 2 consistently show that the lightness effects at the intersections of the grid are captured by the contours, irrespective of the shape of these contours. This effect becomes especially clear in the comparison of the areas surrounding dot 2 and dot 4 (as defined in figure 6) between the straight-contour and the curved-contour conditions. This comparison shows that as a result of curving the contours at the intersection, the area at which the effect is perceived is shifted together with these contours. In other words, the introduction of contours produces areas of different lightness, regardless of their shape and luminance polarity.

To further explore the effect of delineating contours we have made a Hermann-grid like configuration with Geier-like distortions (van Lier and Vergeer 2006). In this configuration, with randomly distorted bars (see figure 8) we drew either black or white lines along the contours and extended these lines to also delineate the intersections.

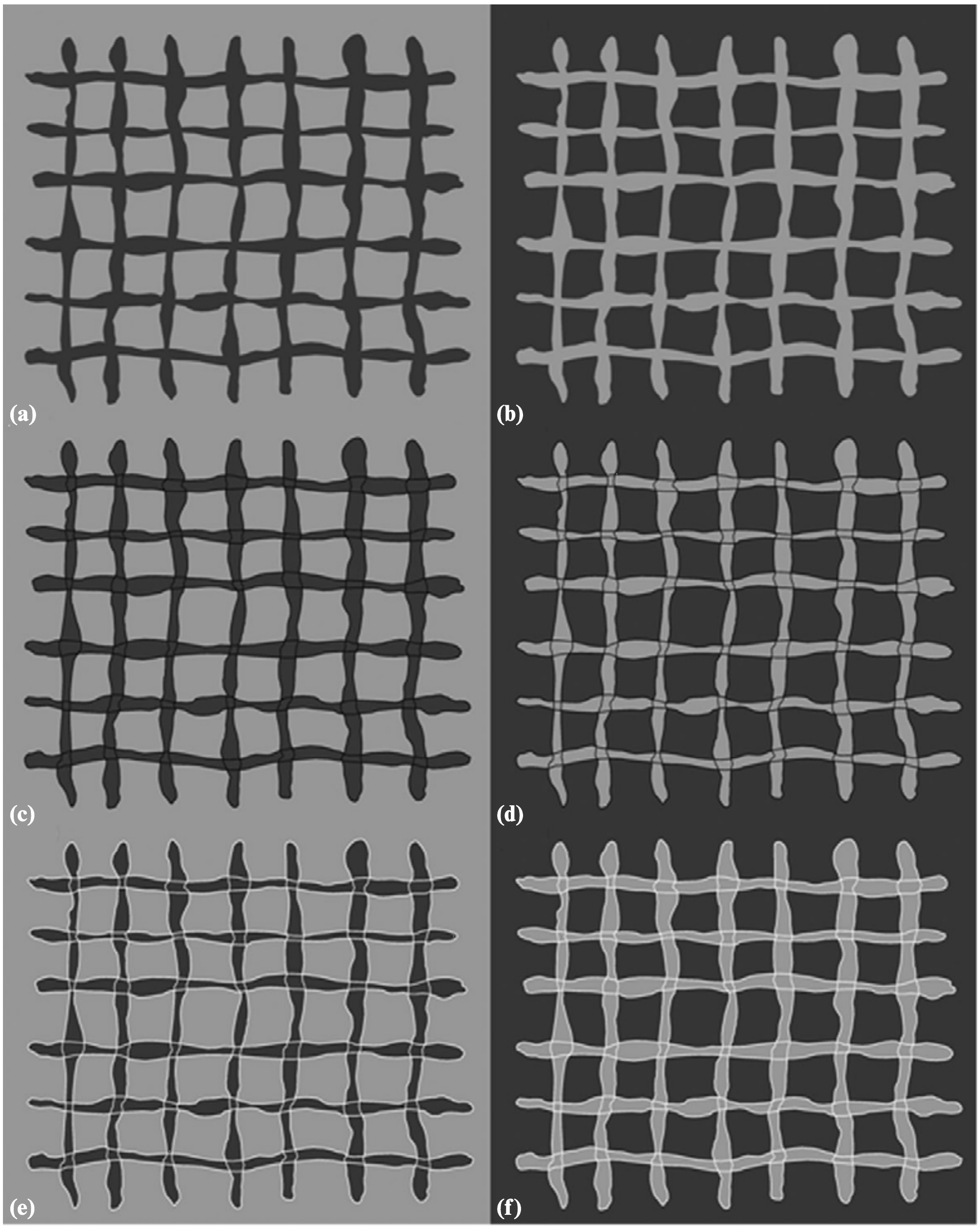


Figure 8. Similar figures are shown on the left and on the right, the only difference being that on the left a dark-grey grid is presented on a light-grey background, while on the right the luminance polarity is reversed. In the upper panels no contours surround the grid. In the middle panels, black contours are presented around the grids and extended across the intersections. As a result, homogenous light patches are perceived at the intersections of the left figure and dark-grey patches are perceived in the right figure. In the bottom figures, white contours are presented in both panels. These white contours do not change the direction of the lightness effects compared to the black contours in the middle panels.

In figure 8a, dark-grey irregular bars intersect each other on a light-grey background. Only weak patches or no patches at all are perceived at the intersections. However, when we add black contours, and extend those contours across the intersections (see figure 8c), the enclosed areas appear to be lighter than the remaining of the bars. In figure 8e, white contours are added, which also leads to the perception of lighter-grey patches at the intersections. On the right, the same has been done for intersecting light-grey bars on a dark-grey background. Again, we start with a grid with no contours (figure 8b), which shows no lightness differences at the intersections. Adding dark contours (figure 8d) or light contours (figure 8f) leads to the perception of darker inner areas at the intersections. As in the previous experiments and observations, the illusory lightness at the crossings is also present in foveal vision and is captured between the contours surrounding the intersections, irrespective of the shape of the contours and their luminance. Again, the direction of the effect (light versus dark) depends on the luminance of the grid relative to the luminance of the background.

To confirm these observations in a more objective way we have presented each of the panels of figure 8 to sixteen naive observers (the stimuli were shown on a CRT monitor; visual angle for each of the panels was ~ 11 deg, the dark-grey and light-grey fields had luminance values of ~ 3 cd m^{-2} and 33 cd m^{-2}, respectively, and the black and white outlines had luminance values of 0 cd m^{-2} and 99.9 cd m^{-2}). Each panel was presented twice. The observers judged the lightness of the intersections in each figure as compared to the remaining of the bars (the intersection appeared lighter than the bars, darker than the bars, or equal to the bars). The observation that presenting contours across the intersections leads to lightness differences between the intersections and the bars (c, e, d, f) was confirmed by the naive observers. In 68% of the observations, lightness differences were reported corresponding to our initial observations, whereas in 28% of the cases in which no contours were presented (a, b) differences were reported corresponding to the expectations in the conditions with contours. Again, the effect was larger for white contours than for black contours (78.1% versus 57.8%). Note that the luminance difference between the black contours and the dark bars was relatively small which may have diminished the effect. These results indicate that the effects for the grids without contours are enhanced by the contours at the intersections. All in all, these observations support our previous findings that surrounding the intersections with contours induces lightness differences in the same direction as seen in the original Hermann grid.

4 General discussion

We have shown that, when outlined, homogeneously coloured bars cross each other, the lightness of the crossing differs from the lightness of the rest of the bars. Light bars on a dark background show darker crossings and dark bars on a light background show lighter crossings. The direction of the lightness difference does not depend on the luminance polarity of the outlines. Moreover, the illusory lightening or darkening of the crossings is also perceived on outlined irregular (non-straight) bars and appears to fill in a randomly shaped area at the crossings. As mentioned, Jung (1973) reported that if the intersections of the Hermann grid are surrounded with outlines, the illusory darkening persists, even in foveal vision (see also Spillmann 1994). There are at least three novel features in our effect compared to Jung's: (i) the direction of the effect (lighter versus darker patches) occurs regardless of the luminance polarity of the contours; (ii) the contours do not have to be straight across the intersection, as the induced lightness appears to spread across the entire outlined area; (iii) the effect also occurs when contours are extended in distorted grids. In the classical Hermann grid illusion the dark spots at the intersections are assumed to stem from lateral inhibition. As the receptive fields of retinal ganglion cells are larger in the periphery, the dark spots are best seen in peripheral vision. Disappearance of the dark spots in Geier et al's distorted grid (2008) points to an additional mechanism in the Hermann grid. According to Schiller and Carvey (2005) S1 type simple cells in primary visual cortex respond to the grid. Unlike retinal ganglion cells, S1 cells have elongated receptive fields. The activity of these cells at the crossing of the Hermann grid as compared to a location between the crossings would account for the spots in the grid. The elongated receptive field would make these cells more susceptible to distortions of the contours of the grid. Geier et al (2008), instead, propose a radiating-edge hypothesis, according to which the whiteness at non-intersecting parts of the Hermann grid is caused by radiation from dark/light edges between the squares and the intermediate bars. They hypothesise that the black edges radiate darkness on their dark side and lightness on their light side. In addition, Geier et al argue that this radiation is related to the straightness and continuity of the edges: "the straighter a continuous edge is, the stronger is the radiation of its elemental segments" (Geier et al 2008, page 660). Since the intersections are less affected by radiation, dark spots are perceived in the Hermann grid. When distortions are made to the cross, radiation would be weaker, as a result of which no patches are perceived at the intersections. The perceived lightness differences due to delineated crossings presented here cannot be accounted for by Geier et al's hypothesis. Their radiating-edge hypothesis may require an additional principle if it is to be applied to our current findings.

We suggest that the current phenomenon can best be explained in terms of simultaneous lightness contrast due to lateral inhibition and an additional spreading and capturing of the induced lightness differences between the outlines that surround the induced area. The present demonstrations and experiments show that induced lightness contrast can indeed be captured between contours, and that this capturing is independent of the luminance polarity and shape of the contours. The luminance polarity between the bars and the background, however, appears to be decisive with respect to the appearance of dark or light patches. We argue that this capturing to a certain extent could also modulate the percept in the classical Hermann grid. Owing to the relatively large receptive field size in peripheral vision, edge detectors at the intersections collinear to the straight contours of the grid squares are activated to a certain extent. This may reveal a partial blocking at the peripheral intersections, resulting in the perceived dark spots at the intersections. Thus, the collinear but interrupted edges at the intersections may act as blocking borders as well, although weaker than would be the case with (real) luminance borders. When distortions are made to the contours of the grid, as in Geier et al's demonstrations, orientation-selective edge detectors are less activated at the intersections, which prevents them from interfering with the spreading of the lateral inhibition effects. However, when contours are drawn at the intersections of these distorted grids, induced lightness contrast is again blocked and captured between the contours.

The interaction between colour and lightness on the one hand and contours on the other hand has been well documented and it has been argued and demonstrated that filling-in occurs by means of a contour-based mechanism operating in early cortical areas (eg Francis 2010; Grossberg 2003; Komatsu 2006; van Lier et al 2009).[(1)]

[(1)] Note that filling-in and lightness appearance may be the result of mechanisms at various stages of the visual process and is not exclusively mediated by contours. For example, perceptual grouping by common motion or symmetry may induce achromatic contrast effects (Agostini and Proffitt 1993) or chromatic assimilation effects (Fuchs 1923; van Lier and Wagemans 1997), respectively. Also depth perception based on local cues may trigger lightness differences (eg in the Kanizsa triangle—see Kogo et al 2010). In addition even visual attention may alter the appearance of surface characteristics (eg Tse 2005).

Such a contour-based filling-in mechanism seems to be responsible for the current phenomena as well. Because the spreading is blocked at the contours, the outlined area at the intersection would maintain a different perceptual quality in terms of lightness. The question whether the actual lightness effect in the Hermann grid is the result of a darkening at the intersections of the grid or of a brightening at the non-intersecting parts of the grid has been addressed before (eg by Spillmann 1994), but no conclusive answer to this question has been given so far. It seems to be impossible to determine an absolute point of reference when it comes to lightness perception, since the lightness we perceive at each single point in space cannot be attributed to one single factor.

Finally, we show that the current phenomenon also appears from a dynamic version of the effect, showing that the induction of the lightness differences between the contours is the result of a rather rapid process (see Supplemental movie 1, http://dx.doi.org/10.1068/p6539). In this movie, a dynamic version of an irregular Hermann grid is shown in which the (irregular) horizontal and vertical bars move in horizontal and vertical directions, respectively. Note that in the dynamic version the shapes of the outlined areas at the intersections are continuously modulated. Despite this modulation, the capturing of the lightness effect within the contours surrounding the intersection seems to occur instantaneously and is maintained over time (Supplemental movie 2 shows an example with different luminance settings).

All in all, the current phenomena show the importance of lightness contour interactions. Effects like simultaneous lightness contrast evoked by lateral inhibition spread across a surface and are additionally blocked by contours. In other words, the phenomena presented here are a clear demonstration that lightness effects can be captured between contours.

Supplementary movies

Both movies show irregular outlined bars that dynamically cross each other. Note that the lightness differences at the intersections seem to appear instantly.

Acknowledgments. MV was supported by NWO grant 400-03-406 awarded to RvL. The panels in figure 8 and supplementary movie files were previously nominated in the Best Visual Illusion Contest (van Lier and Vergeer 2006). The authors would like to thank Lothar Spillmann, Daniele Zavagno, and János Geier for their valuable comments on a previous version of this manuscript.

References

Agostini T, Proffitt D, 1993 "Perceptual organization evokes simultaneous lightness contrast" *Perception* **22** 263 – 272

Baumgartner G, 1960 "Indirekte Grössenbestimmung der rezeptiven Felder der Retina beim Menschen mittels der Hermannschen Gittertäuschung" *Pflüger Archiv für die gesamte Physiologie des Menschen und der Tiere* **272** 21 – 22

Francis G, 2010 "Modeling filling-in of afterimages" *Attention, Perception, & Psychophysics* **72** 19 – 22

Fuchs W, 1923 "Experimentelle Untersuchungen über die Änderung von Farben unter dem Einfluss von Gestalten (Angleichungserscheinungen) [Experimental investigations on the change of colour under the influence of Gestalten]" *Zeitschrift für Psychologie* **92** 249 – 325

Geier J, Bernáth L, Hudák M, Séra L, 2008 "Straightness as the main factor on the Hermann grid illusion" *Perception* **37** 651 – 665

Geier J, Séra L, Bernáth L, 2004 "Stopping the Hermann grid illusion by simple sine distortion" *Perception* **33** Supplement, 103

Grossberg S, 2003 "Filling-in the forms: Surface and boundary interactions in visual cortex", in *Filling-In: From Perceptual Completion to Cortical Reorganization* Eds L Pessoa, P de Weerd (Oxford: Oxford University Press) pp 13 – 37

Hamburger K, Shapiro A G, 2009 "Spillmann's weaves are more resilient than Hermann's grid" *Vision Research* **49** 2121 – 2130

Hering E, 1874/1964 "Von simultanen Grenzkontrast", in *Grundzüge der Lehre vom Lichtsinne* (1874, Berlin: Springer) [translated from German by L M Hurvich, D Jameson *Outlines of the Theory of the Light Sense* (1964, Cambridge, MA: Harvard University Press)]

Hermann L, 1870 "Eine Erscheinung des simultanen Contrastes" *Pflügers Archiv für die gesamte Physiologie* **3** 13 – 15
Jung R, 1973 "Visual perception and neurophysiology", in *Handbook of Sensory Physiology* volume V11/3 A, Ed. R Jung (Berlin: Springer) pp 1 – 152
Komatsu H, 2006 "The neural mechanisms of perceptual filling-in" *Nature Reviews Neuroscience* **7** 220 – 231
Kogo N, Strecha C, Van Gool L, Wagemans J, 2010 "Surface construction by a 2-D differentiation – integration process: A neurocomputational model for perceived border ownership, depth, and lightness in Kanizsa figures" *Psychological Review* **117** 406 – 439
Kuffler S W, 1953 "Discharge patterns and functional organization of mammalian retina" *Journal of Neurophysiology* **16** 37 – 68
Lier R van, 2002 "A double neon colour illusion" *Perception* **31** 31 – 38
Lier R van, Wagemans J, 1997 "Perceptual grouping measured by color assimilation: Regularity versus proximity" *Acta Psychologica* **97** 37 – 70
Lier R van, Vergeer M, 2006 "Catching patches: Filling-in between edges" *Perception* **35** Supplement, 47
Lier R van, Vergeer M, Anstis S, 2009 "Filling-in afterimage colors between the lines" *Current Biology* **19** R323 – R324
Lingelbach B, Block B, Hatzky B, Reisinger E, 1985 "The Hermann grid illusion—retinal or cortical?" *Perception* **14** Supplement, 7 (abstract)
Schiller P H, Carvey C E, 2005 "The Hermann grid revisited" *Perception* **34** 1375 – 1397
Spillmann L, 1994 "The Hermann grid illusion: a tool for studying human perceptive field organization" *Perception* **23** 691 – 708
Spillmann L, Levine J, 1971 "Contrast enhancement in a Hermann grid with variable figure – ground ratio" *Experimental Brain Research* **13** 547 – 559
Tse P, 2005 "Voluntary attention modulates the brightness of overlapping transparent surfaces" *Vision Research* **45** 1095 – 1098
Werblin F S, Dowling J E, 1969 "Organization of the retina of the mudpuppy. *Necturus Maculosis*— II. Intracellular recording" *Journal of Neurophysiology* **32** 339 – 355

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 39 2010

www.perceptionweb.com