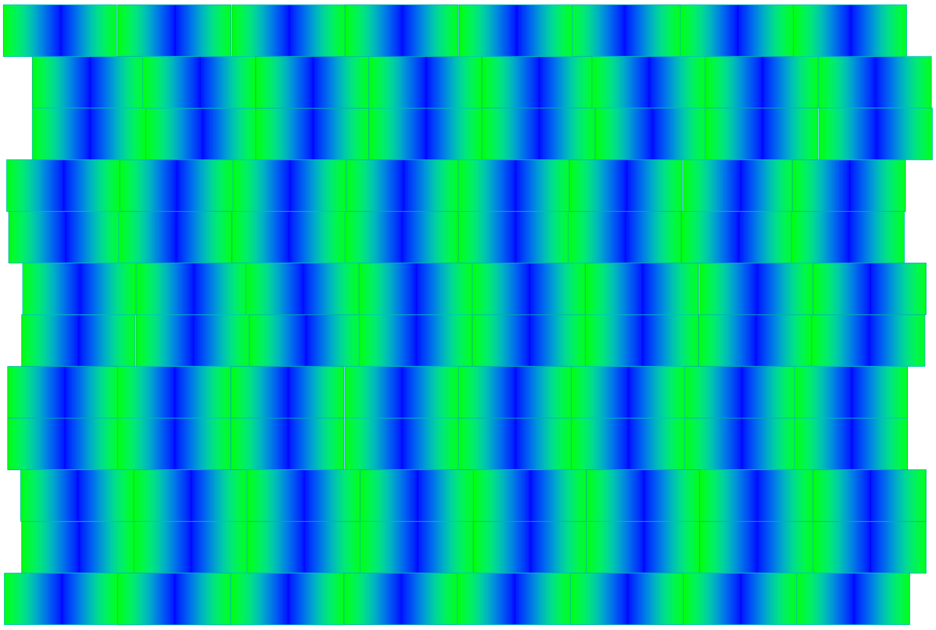
Subjective contours triggered by border lines below the resolution limit



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1. The Problem

There are optical illusions and genuine visual illusions. While the former are entirely due to optical phenomena like refraction (e.g., a mirage), genuine illusions are the product of the cognitive process itself and as such, are frequently difficult to explain conclusively. However, it is common knowledge that when normal subjects are confronted with a particular visual illusion they generally experience very similar effects. It would seem therefore, that in order to investigate visual illusions effectively at least two sources must be considered. The physical or optical properties of the stimulus where the effect is observed and also the data processing involved in the visual system which reacts to optimize the information received.

The Münsterberg (1897) illusion is triggered by two vertical rows of alternating black and white squares which are shifted against each other and oriented along a common black line. This line appears slanted (Fig. 1). The classic Café wall illusion (Fraser, 1908; Gregory and Heard, 1979; Moulden and Renshaw, 1979) is observed on several pairs of parallel rows of alternating black and white rectangles. If, within each pair, the rows are slightly shifted with respect to each other, a wedge distortion is created causing the rectangles to appear mortar shaped. Grey lines separating the rows enhance the effect due to luminance contrast, i.e., a grey line appears brighter under the influence of adjacent dark areas and vice versa (eg, McCourt, 1983; Morgan & Molden, 1986). This occurs, even when the true contour lines are faint and not clearly resolvable, but still visible.

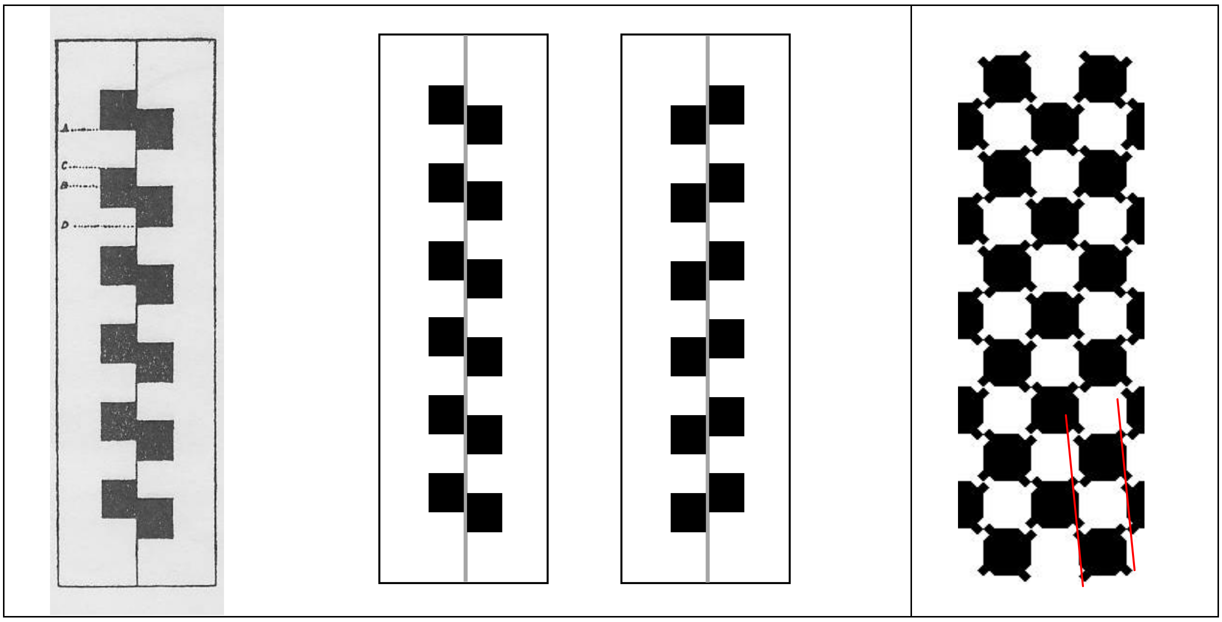

Fig. 1. Left: Original Muensterberg (1897) illusion: Two vertical rows of black squares on white background. A faint black line divides the white background, giving the impression of white squares alternating with the black ones. Middle: A bold grey line is separating the squares. The illusion appears to be slightly enhanced. Right: Illusion of fringed edges, by Kitaoka (2007). Subjective lines, slanted with respect to the vertical/horizontal, are connecting each two of the tiny white or black squares at the corners of the large ones (indicated by red lines).

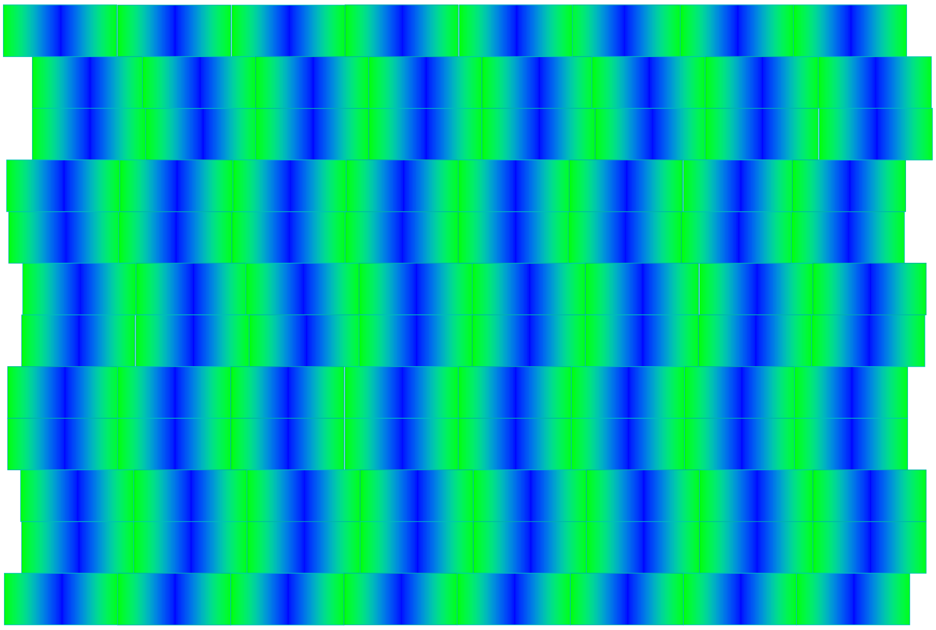

Fig. 2. Example of the Café Wall illusion using colored shading (blue, 256, and green, 256; RGB units) instead of black and white tiles. The color of the contour line is between the blue and the green (b:180; g: 180). Due to Gregory (1977), the intensity of the illusion depends on the luminance contrast between the contour lines and the adjacent areas only.

When referring to the role narrow lines play in this context, one has to define the terms “resolvability” and “perceptibility”. Resolvability is the condition in which the images of two objects can be recognized as being two separate entities, for example, two dots or two faint parallel lines. The resolving power of the human visual system is about 1 minute of arc. However, one can recognize isolated objects which lie within this limit. For example, the diameters of individual stars subtend an angle less than one second of arc, nevertheless, one can see them (just not the exact image which would follow from geometrical optics). This is the consequence of diffraction and other optical effects which broaden the image of an object, simultaneously blurring it and lowering its contrast. Therefore, an isolated faint black line on white background appears grey. However, one can see it, even if it may not be possible to resolve its edges clearly. Observed from a certain distance, even a bold black line can give the impression of being grey.

Things are slightly different with a grey contour line separating a black from a white area (Fermüller 2004). As long as the width of a contour line can be clearly resolved, its edges are just smoothed. However, if the line is so narrow that it can no longer be resolved, the perceived border (which coincides with the first derivative of the perceived intensity profile; Canny 1986) is slightly shifted towards the dark, but, at most, by only one line width (Kreiner 2006). This contributes to the illusion given in Fig. 3 (right). The horizontal contour lines appear to be bent and shifted towards the black. A grey line sandwiched by two black areas (Fig. 3, left) appears considerably brighter than on white background (Wirtz, 2000, 2001).

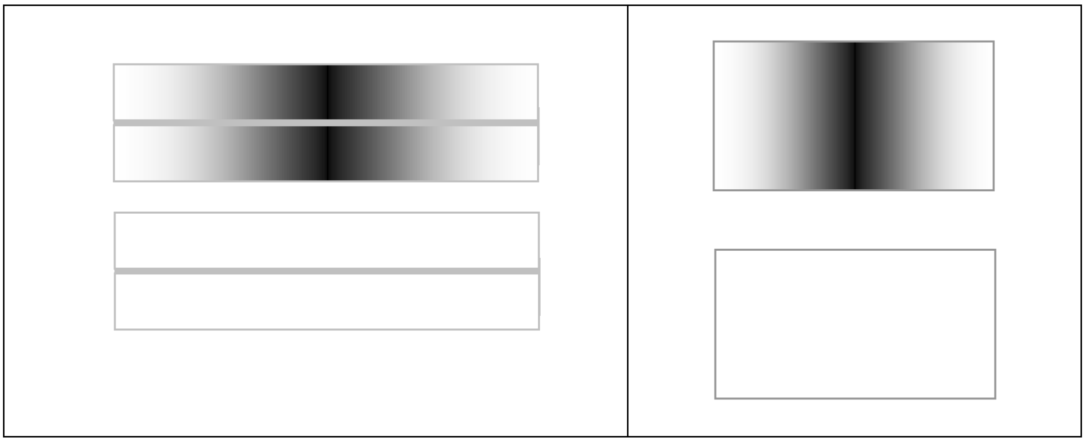

Fig. 3. Left: Induced brightness. Dark surrounding causes a grey line to appear considerably brighter. At the right, a grey line appears to be bent towards the dark domain, reducing the apparent height of the rectangle there.

Concerning the Café Wall illusion, it was pointed out by McCourt (1983) that the visual system creates virtual lines by connecting domains of similar brightness, taking the virtual lines for the true contour lines. They are termed subjective contours. Different designs of patterns were proposed by Kitaoka, Pinna, and Breistaff (2004). Fig. 2 gives a colored variant of the classic illusion. Due to Gregory (1977), the illusion does not persist under conditions of isoluminance. Its intensity rather depends on the luminance contrast between the contour lines and the adjacent areas.

We concentrated on a black and white design. In order to investigate the effect of apparent luminance contrast quantitatively we have used a version with only one kind of tiles (Kreiner, 2008). Details are shown in Fig. 4, where the shading of a single tile varies from white to black and to white again (The saw tooth pattern given by Kitaoka (2007) shows shading from white to black). Dark areas adjacent to the grey line will induce the luminance contrast effect and cause the border line to appear brighter there. However, there will be a domain of comparable hue within the shaded pattern on the adjacent tiles, facilitating the formation of a subjective contour which will be inclined with respect to the true contour line. There is an additional cause which may alter the apparent luminance of the contour line: If its width falls below about one minute of arc ($=2.91\cdot10^{-4}$ rad), the human eye cannot clearly resolve it any more. Due to diffraction, the line will be broadened and blurred, its hue being adjusted to that of the adjacent area. In addition, it will become more difficult to recognize its exact orientation, which, in turn, supports the creation of a subjective contour. Gregory and Heard (1979) have investigated the illusion at mortar line widths above 1 min of arc. The question arises how the intensity of the illusion would depend on the width of the contour line at line widths *below one minute of arc* and what would be the optimum hue. Therefore the experiments were designed to vary the distance of observation, the line width and the hue (in percentage of grey).

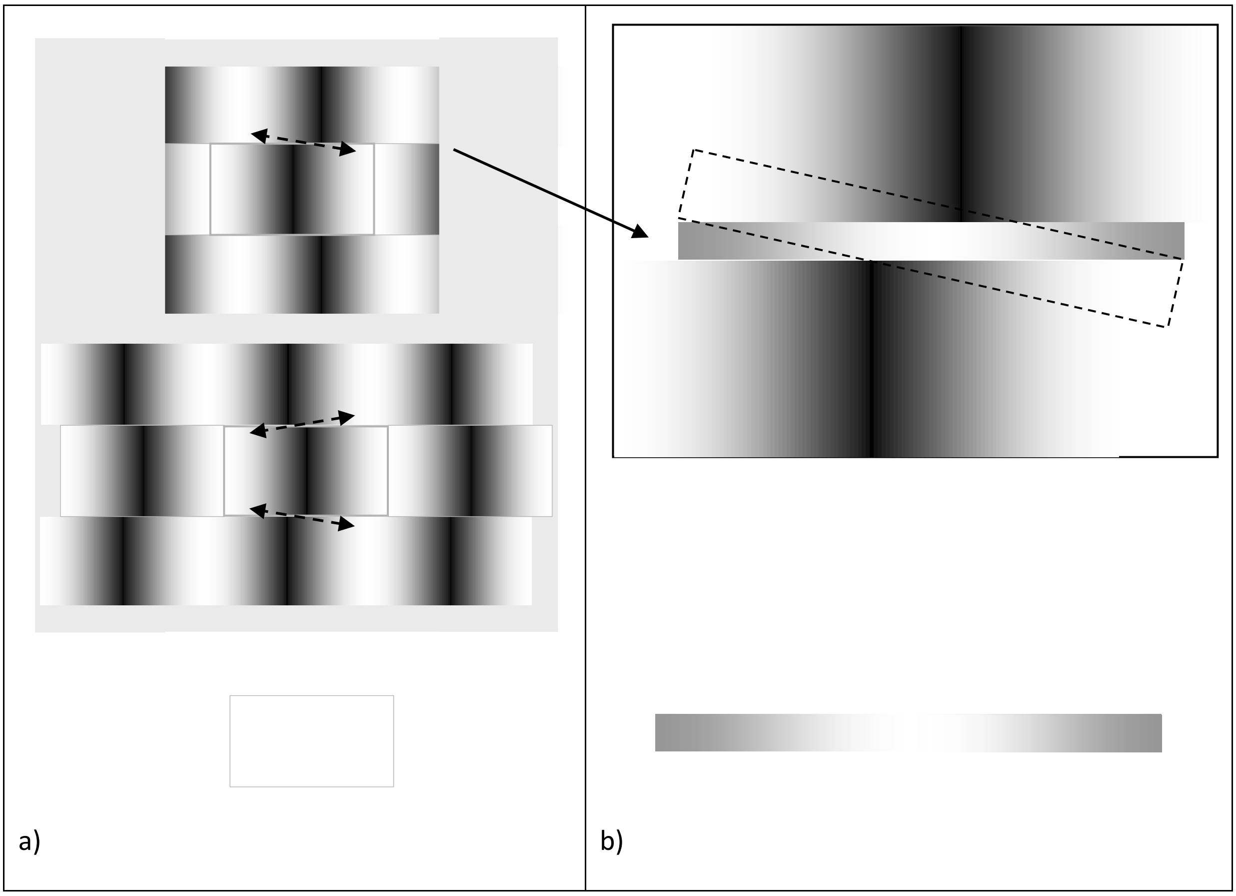

Fig. 4. Slanting border line illusion. Due do McCourt (1983) the visual system forms subjective contours by connecting spots of similar subjective brightness. a) The horizontal border lines of the rectangles (30% grey) appear brighter next to dark areas above and below (induced brightness). Connecting this spot with domains of comparable brightness within the shaded area gives the impression of a slanting border line, pointing slightly downwards and upwards, respectively. Relative positions of the dark domains of adjacent rows determine the degree of inclination. At the bottom, a tile without shading is shown for comparison. In Fig. b), for clarity, the situation is exaggerated. The border line is widened and its luminance is purposely enhanced in the middle. The same contour line is given underneath.

2. Experiment

2.1 *Subjects.* 6 healthy volunteers, age between 48 and 64 took part, among them the author. Five of them were naive.

2.2 *Stimuli.* Each stimulus showed three rows of five rectangles, shadowed from white to black and back to white again (Fig. 5 gives three examples). The middle row was shifted to the left by 6.3 % of its length. Only this row had a contour line. The width of the contour line was 0.25 / 0.5 / 0.75 / 1 / 1.5 / 2.25 / 3 / 4.5 / and 6 pt (PostScript points=0.353mm), their hue 20%, 40%, 50%, and 80% grey, or black. To the left, on a separate sheet, seven quadrangles were shown arranged in a column, serving as standards. The lowest one was of rectangular shape, the others trapezoids with increasing wedge angle from bottom to top. The transparencies were printed on white glossy cardboard of size DIN A4 and pinned to a white board. One more example of an illusion of this family is given in the appendix.

2.3 <u>*Procedure.*</u> The subjects, one by one, watched the stimuli for a few seconds and indicated which of the standards seemed to match the perceived shape of the elements in the middle row. There was no time limit imposed. Distance of observation was varied from 1 to 5m, in steps of 1m.

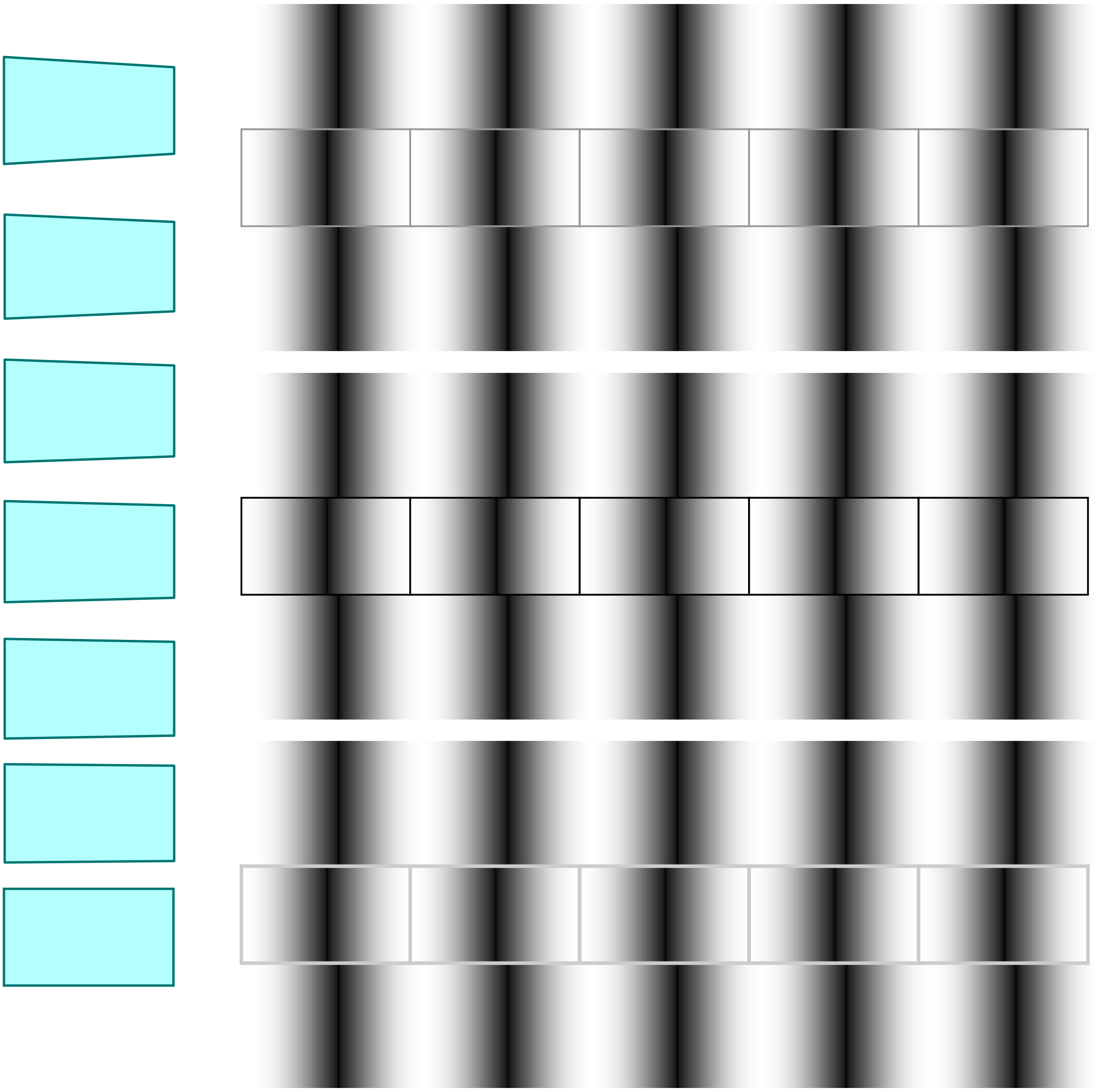

Fig. 5. Examples of stimuli. Top: Contour line is 0.75 pt. wide and 40% grey. Middle: Same width, black. There is hardly any effect to be seen. Bottom: 1.5 pt wide, 20% grey. In this case, the illusion is clearly to be seen when watched from a distance of about two meters. At the left, the seven wedges presented as standards. Wedge angle (deviation of the upper or lower side from the horizontal) ranged from zero to $60 \cdot 10^{-3}$ rad.

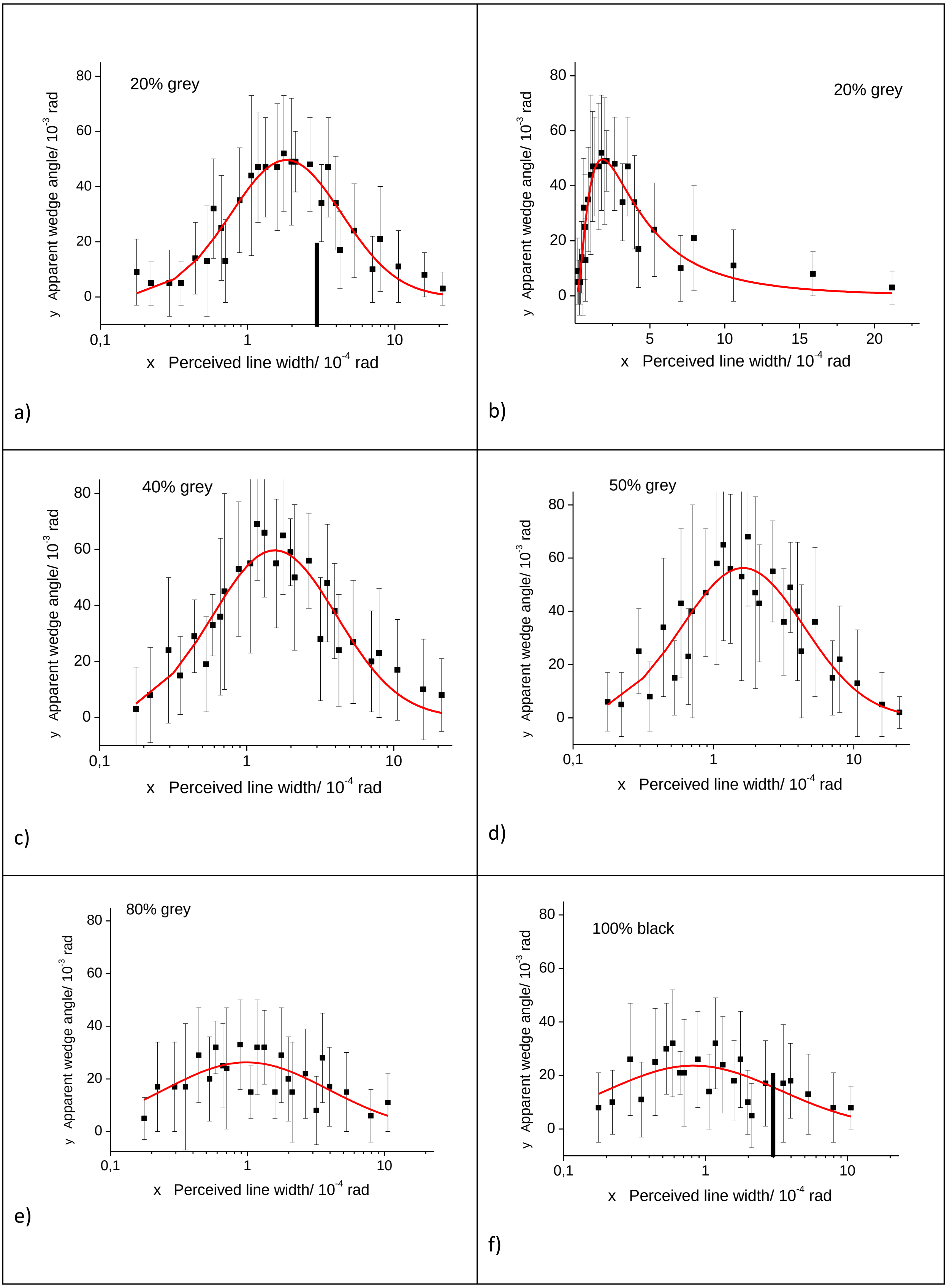

Fig. 6. Plots of the perceived shape (in units of the apparent wedge angle) versus the angle subtended by the width of the contour line which was varied between 0.18 and 21.17x10^{-4} rad. For the x-axis, a logarithmic scale was chosen (except b). The values for 20% grey are shown above a linear scale, too. The illusion peaks below the resolution limit of the eye, indicated by the bold vertical marker (= 1 minute of arc = 2.91x10^{-4} rad).

2.4 *Evaluation.* In total 48 data were collected from each person. Due to the experimental procedure there were several data referring to the same effective line width; e.g., a contour line, 1.5 pt wide observed from a distance of 2m subtends the same visual angle as a line, 3 pt wide, at a distance of 4m. In the first step of evaluation, all equivalent data were averaged, resulting in 28 data per person utmost.

2.5 *Results.* Fig. 6 gives the perceived wedge angle in units of 10^{-3} rad for five different hues as a function of the effective line width of the contour (in units of 10^{-4} rad). The vertical grey bar indicates the resolution limit of the eye (1 minute of arc $=2.91 \cdot 10^{-4}$ rad). In all experiments the maximum of the illusion is found to be below this mark. For 80% grey and for black the peak is slightly shifted to even lower values of the line width (e and f).

2.6 *Fitting the mathematical function.*

A lognormal function seemed to be suitable for the fitting procedure:

$$\boxed{y = A*\exp[-B*(\log(x/C)^2)]}$$

where A means the maximum of the function and C the position of the maximum along the x-axis. The constants are collected in Table 1, below. In order to show the measured values well separated, a logarithmic scale was chosen in Fig. 6 for the effective line width (x-axis).

Table 1	20% grey	40%	50%	80%	black
A	49.6(23)	59.7(26)	56.3(30)	26.3(21)	23.7(22)
B	0.663(81)	0.527(63)	0.495(72)	0.263(81)	0.250(94)
C	1.830(90)	1.549(81)	1.62(11)	0.98(16)	0.82(17)

3. Discussion

From the results one can draw the conclusion that the illusion gains its maximum when the contour line is so narrow that it cannot be clearly resolved and recognized any more but, on the other hand, still can induce the brightness effect. The line then appears to be blurred, but can still exhibit subjectively bright and dark domains to trigger the illusion. However, a very narrow a line cannot be differentiated any more from its surroundings (due to diffraction) and hardly any brightness induction would occur. Contour lines considerably above the resolution limit of the eye cannot be replaced by subjective contours, because their edges and orientation can be clearly recognized. Therefore, a maximum of the illusion will occur when the widths of the grey border line subtends a certain angle. Black as well as very bright contour lines are less likely to trigger the illusion, because brightness induction will be less effective.

Citations

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4. Appendix

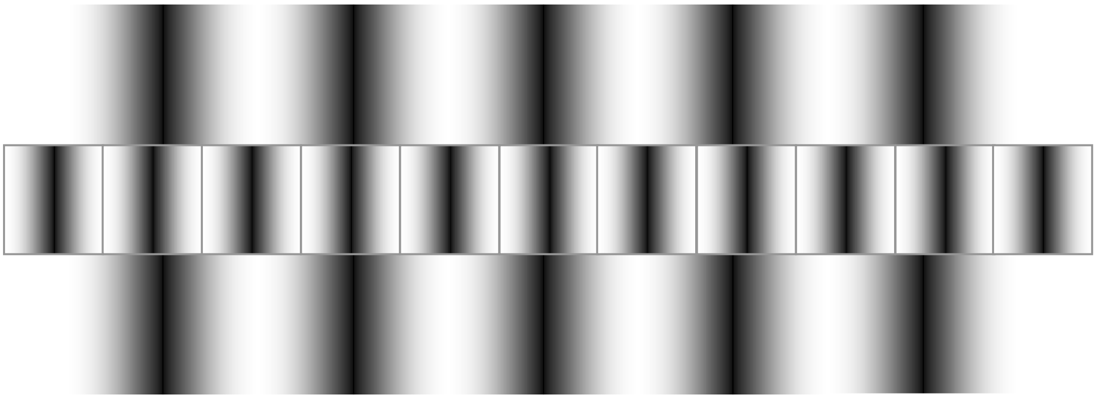

Fig. A1. Variant of the Münsterberg/Café Wall illusion giving the impression of a wave like line. To achieve this, the rectangles in the middle row were shortened by 48% with respect to the context elements above and below.